# Noise Figures, Noise Temperatures, and System Sensitivity

by
P. H. Enslow, Jr.

Technical Report No. 516-2
July 10, 1961



PREPARED UNDER
SIGNAL CORPS CONTRACT DA36(039)SC-78296



SYSTEMS TECHNIQUES LABORATORY
STANFORD ELECTRONICS LABORATORIES
STANFORD UNIVERSITY · STANFORD, CALIFORNIA

# ERRATA

| Page | |
|---|---|
| vi | Item C should read: Effect of intermediate-frequency image... |
| ix | Last item should read: $\overline{F}$ Network noise factor... |
| xi | First item should read: $P_{WF\ min}$ Signal power... |
| 4 | Line 2 should read: 1. OUTPUT NOISE POWER. An <u>ideal</u> network <u>adds</u> no noise power to... |
| 5 | Footnote should read: ... Section IX.B.3.b., p. 71. |
| 12 | Eq. (3.2) denominator should read: $$\int_0^\infty G(f)\, df$$ |
| 13 | Line 21 should read: The definition given above for $\overline{F}$ may be... |
| 25 | Fig. 3.5. Label above arrow at right should read: $S_o = G_o S_1$ |
| 26 | Line 8 should read: $\overline{F}_{M-IF}$ = "standard" noise factor of the crystal mixer i-f amplifier... |
| 27 | Fig. 3.6. Expression in lower box should read: $(t_r T_o - G_o T_s)kB$<br>Label below arrow at right should read: $$N_o = kT_s\ BG_o + (t_r T_o - G_o T_s)kB$$<br>Last line of footnote should read: where $t_{eff}$ = "effective input"... |
| 30 | Fig. 3.8. Expression in lower box should read: $kt_{ex}\ T_o B$<br>Equation below arrow at right should read: $$N_o = kT_s\ BG_o + kt_{ex}\ T_o B$$ |
| 36 | Last line should read: $$\overline{F}_{op} \neq \frac{(S_i/N_i)}{(S_o/N_o)}$$ |
| 43 | Eq. (3.49), numerator should read: $\gamma T_{rad} + (1 - \gamma)T_{amb}$ |
| 50 | Eq. (5.12), denominator of last fraction should read: $$G_{o_1}\ G_{o_2} \cdots G_{(n-1)}$$ |
| 52 | Fig. 5.2. Expression in lower left box should read: $$(t_{r1} - G_{01})\ kT_0\ B_1$$ |

ERRATA (Continued)

Page

53 Line 10 should read: From Eq. (5.15) above,..

66 Fig. 8.3. Expression in bottom center box should read:

$$(t_{r_M} - G_{0_M})\, kT_0$$

Last line of legend (B) should read: ...noise temperature ratio $t_r$.

90 Line 14 should read: ... mixer. See footnote page 88.

NOISE FIGURES, NOISE TEMPERATURES, AND SYSTEM SENSITIVITY

by

Philip H. Enslow, Jr
Captain, Signal Corps, U.S. Army

Technical Report No. 516-2
July 10, 1961



Prepared under
Signal Corps Contract DA36(039)SC-78226

Systems Techniques Laboratory
Stanford Electronics Laboratories
Stanford University
Stanford, California

# SUMMARY

The definitions of terms used in systems noise work are presented, as well as general techniques of describing noise power resulting from both the source and the excess noise added by the network under consideration. A unique feature of this report is a unified development of seven "noise temperatures" encountered in this field, with tables showing the relationships among them and their uses. A general technique for calculating the sensitivity of a receiver is presented and three examples are treated in detail: the simple crystal-video system, the crystal-video receiver with r-f preamplification, and the superheterodyne system. All systems are divided into two classes for which the calculations are similar: receivers having only a simple detector, and those having some form of linear amplification preceding the detector. The final analysis of the noise performance of the system requires a comparison of the pre-detection and post-detection excess noise. This comparison is performed by referring all excess noise power to the detector input and classifying the system according to whether (a) the pre-detection noise predominates, (b) the post-detection noise predominates, or (c) the pre-detection noise and the post-detection noise are comparable in magnitude.

The Appendices cover several topics of interest, such as image response and the special problems encountered with a panoramic receiver.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

## TABLE OF CONTENTS (Cont'd)



## LIST OF CHARTS



## LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Cont'd)

## LIST OF SYMBOLS

| | |
|---|---|
| $A$ | Capture area of antenna. (Must have same units of area as $P_{WF}$.) |
| $b$ | Network 3-db bandiwdth. |
| $B$ | Network noise bandwidth. $$B = \frac{1}{G_0} \int_0^{\infty} G(f)df$$ |
| $B_{eff}$ | System effective bandwidth. |
| $B'_{eff}$ | Effective bandwidth of the <u>linear</u> <u>pre-detection</u> portion of a receiver. |
| $b_{VM}$ | Video amplifier bandwidth at which detector-video-amplifier sensitivity was measured. |
| $D$ | Noise power density at detector input attributed to the linear system, watts/cycle. |
| $D_e$ | Equivalent noise power density at detector input attributed to detector-video-amplifier noise, watts/cycle. |
| $\overline{e_n^2}$ | Mean square value of thermal noise voltage. |
| $(\overline{EN})$ | External noise factor (ratio). |
| $f_{IF}$ | Intermediate-frequency amplifier center frequency. |
| $f_{LO}$ | Local oscillator frequency. |
| $\Delta f$ | Width of frequency band swept by the local oscillator. |
| $\Delta f'$ | Width of desired band plus image band included in passband. |
| $F$ | Network noise factor (noise figure) at a given operating point and input frequency. Commonly called the "spot noise factor". Referred to the standard temperature, 290°K, unless otherwise specified by a subscript. |
| $\overline{F}$ | Netowrk noise factor averaged over the network frequency range. $$\overline{F} = \frac{\int F(f)G(f)df}{\int G(f)df} \quad T_s = T_0$$ |

| | |
|---|---|
| $F_0$ | Network optimum noise factor at a given operating point and frequency. Lowest noise factor that can be obtained through adjustment of the source admittance. |
| $F_{Op}$ | Network average operating noise factor. |
| $F_s$ | Network average effective noise factor (referred to the source temperature). |
| $F_{12}$ | Noise factor of networks No. 1 and No. 2 in cascade. |
| $F_{1-n}$ | Noise factor of networks 1 to n in cascade. |
| $F^*$ | Excess noise factor. Used in cascaded network formulas. |
| G | Network gain $g = S_0/S_i$ |
| G(f) | Available network power gain at frequency f. |
| $G_0$ | Available gain at some convenient reference frequency, $f_0$; usually frequency of maximum response. |
| k | Boltzmann's constant: $1.374 \times 10^{-23}$ joule/$^\circ$C; $10 \log_{10} k = -228.6$. |
| K | Constant describing gain of detector/video-amplifier combination. |
| L | Network loss $L = \frac{1}{G}$ |
| $N_a$ | Available noise power. Normally refers to kTB thermal noise. |
| $N_i$ | Network input noise power, watts. |
| $N_0$ | Network total output noise power, watts. |
| $N_0'$ | Network output noise power attributed to amplified input noise, watts. |
| $N_0''$ | Network output noise power attributed to excess network noise, watts. |
| $P_{s\,min}$ | Signal power required to meet "minimum detectable signal" criterion at output, referred to receiver input terminals. |
| $P'_{s\,min}$ | Signal power required to meet "minimum detectable signal" criterion at output, referred to detector input. |

| | |
|---|---|
| $P_{wf\ min}$ | Signal power required in wave front per unit area at receiving antenna to meet "minimum detectable signal" criterion at output. (Units of area same as for A.) |
| $R$ | Resistive component of an element. |
| $S_i$ | Network input signal power. |
| $S_o$ | Network output signal power. |
| $S_x$ | Sensitivity of detector/video-amplifier combination as measured at the detector input. |
| $t_{ex}$ | Excess-noise: temperature ratio. |
| $t_r$ | Noise temperature ratio. |
| $\Delta T$ | Period of one frequency sweep by the local oscillator in the repetitive-sweeping panoramic receiver. |
| $T_A$ | Equivalent temperature of the antenna resistance, both radiation and ohmic considered together. |
| $T_{amb}$ | Temperature of the surroundings and equipment. |
| $T_{app}$ | Apparent temperature seen by system when the system effective noise temperature is added to the source temperature, $T_s$. |
| $T_e$ | Effective noise temperature. Refers to <u>excess</u> noise. Used by radio astronomers. |
| $T_{eq}$ | Equivalent noise temperature. Refers to <u>total</u> noise output of network. |
| $T_o$ | Standard temperature: $290^{o}K$, $17^{o}C$. |
| $T_{rad}$ | Equivalent temperature of the radiation resistance of an antenna. |
| $T_s$ | Temperature of the source as seen by the network. Often refers to the noise source discharge temperature. |
| $T_s - T_o$ | Excess noise temperature of the source. |
| $T_s/T_o$ | Relative noise temperature of the source. |
| $\dfrac{T_s - T_o}{T_o}$ | Relative excess noise temperature of the source. |

## LIST OF SYMBOLS (Cont'd)

| | |
|---|---|
| $X$ | Reactive component of an element. |
| $X_A$ | Reactive component of the antenna. |
| $\gamma$ | Antenna radiation efficiency. |

Subscripts Used in Referring to Various Network Elements:

| | |
|---|---|
| A | Antenna |
| BP | r-f bandpass |
| D | Detector |
| IF | i-f amplifier |
| L | Linear portion of receiver, i.e., receiver input terminals to detector input. |
| LO | Local oscillator. |
| M | Mixer. |
| PA | r-f preamplifier. |
| PS | r-f preselector. |
| TL | Transmission line. |
| V | Video amplifier. |

## DISCLAIMER

Opinions and assertions contained herein are the private ones of the author and are not to be construed as official or necessarily reflecting the views of the United States Army Signal Corps or of the military service at large.

## ACKNOWLEDGMENT

The author would like to express his appreciation to the editors of the "Hewlett-Packard Journal" for permission to reprint Chart III-1 and to the Institute of Radio Engineers for permission to reprint Chart III-2. Mr. Donald J. Grace has been extremely helpful during the course of this study, and it is primarily through his interest that this report was completed. The author would also like to thank the many other members of the Stanford Electronics Laboratory faculty and staff who gave freely of their time to discuss this subject. This work was initiated while the author was taking graduate training at Stanford University under the auspices of the United States Army Signal Corps and completed while the author was stationed in Korea following his graduate studies.

## PART ONE --- INTRODUCTION

### I. THE PROBLEM

During the course of a project which was undertaken to investigate some of the systems design considerations of frequency-scanning micro-wave radar intercept receivers, it became increasingly apparent that a detailed understanding of system and component noise, as well as related problems, is of major importance. Of particular interest in the larger study was the maximum over-all sensitivity that could be expected from a receiver system, and it was desired to be able to estimate the value of this characteristic from a "paper study" of the system.

As the original study progressed, a greater appreciation of some of the more subtle points in considering noise was developed; but these techniques and problems are not unique to the intercept receiver. In order to permit a better dissemination of the material on noise alone, the noise section has been extracted from the study of intercept receivers and is presented here as a separate report. An attempt has been made to keep this material as general as possible. At times, however, this was not possible; and the particular examples used in such cases are those that were of prime interest in the original study.

An engineer is usually able to estimate the order of magnitude of the sensitivity of a system before he constructs it, but more often than not there is a wide discrepancy between the calculations and the actual measured performance. In fact, it is often difficult to calculate the measured sensitivity even after the equipment has been built. Usually some of the difference can be traced to an obscure point that was overlooked. One of the purposes of this study was to bring out some of these finer details as well as to present a very general technique for making sensitivity calculations. It certainly cannot be expected that the calculations will agree precisely with the actual performance, nor is this absolutely necessary; but the computed values should be as close as possible (perhaps 3-db difference would be an acceptable standard in some cases). It was with this point of view that the following study was prepared. The sensitivity criterion used throughout this report is the "minimum detectable signal"; though other definitions are possible, the techniques would be the same regardless of the criterion employed.

The definitions and descriptions of network noise and calculations of system sensitivity are very confused topics in present day literature. It is hoped that this report will represent a complete and consistent discussion of these matters.

The body of the report is divided into two major parts. The first part is concerned with very general topics such as definitions and methods of expressing noise power. The unified development of the various noise temperatures presented here is believed to be unique in this field. Although this topic is very confusing when it is first encountered, it is hoped that the presentation here will give the reader some insight into the origin and significance of the various "noise temperatures". There are very possibly some "temperatures" that are not included and certainly many other names for those that are presented here, but the seven which are discussed are the ones most commonly encountered. The complete discussion of noise figures and noise temperatures is intended to provide a thorough guide to the literature on this topic.

The second portion of the report provides practical application of the definitions and techniques presented in the first part, while describing the methods pertinent to computation of component and system sensitivity.

Finally, the appendices treat several topics of importance in making sensitivity calculations which did not fit into the main body of the report.

PART TWO --- NETWORK NOISE

# II. INTRODUCTION

## A. GENERAL

The magnitude of the total system output noise is extremely important in the analysis of any sensing or recording system. It is this quantity in combination with the system gain which determines the minimum signal strength that it will be possible to detect. As will be seen in the development that follows, the noise performance (noisiness) and gains of the various stages may be such that the over-all system noise is effectively determined by the first one or two stages. The complete development of the relationships defining the over-all system noise will enable the systems engineer to know the essential conditions for which this approximation can apply. Before it is possible to look at any system as a whole, though, it is important to examine first the individual types of networks and to become familiar with the various methods of treating noise in each stage. This section will present some basic definitions which will be elaborated on and employed in the following section which is concerned with the various ways of describing the "noisiness" of a network.

The main body of this report will consider only the noise in the single "signal" channel. A method for including "image channel" noise in a superheterodyne receiver, or noise in any other "channel", is presented in Appendix C.

Most of the material presented in this section can be found in the literature. In fact, more complete discussions of many of the finer points are available there. The purpose of including this material here is to introduce a new and unified approach to the entire problem while explaining the notation that will be followed in the remainder of the study.

## B. THE COMPONENTS OF NETWORK NOISE

1. OUTPUT NOISE POWER. An ideal network adds to noise power to the output. The only noise present in the output results from amplifying the input noise power. However, with the possible exception of recent developments in maser amplifiers, a large amount of excess noise power is added to the output signal by every active network. The excess noise added may be generated in many ways: shot noise in a tube, noise in an electron beam, semiconductor noise, or even noise from a passive attenuator.

$$\begin{bmatrix}\text{Network total}\\ \text{output noise}\\ \text{power}\end{bmatrix} = \begin{bmatrix}\text{Amplified}\\ \text{input noise}\\ \text{power}\end{bmatrix} + \begin{bmatrix}\text{Excess noise}\\ \text{power added}\\ \text{by the network}\end{bmatrix} \qquad (2.1)$$

In Part Two of this report the topic of primary concern is how to describe the three terms given in the equation above.

2. INPUT NOISE POWER.

a. Available noise power from a resistive source. The random nature of the motion of free electrons in a resistive element gives rise to a fluctuating voltage which appears across the terminals of the resistor. This fluctuation is known as "thermal noise" or "Johnson noise."[9*]

The value of this voltage has been found to be

$$\overline{e_n^2} = 4\,k\,T_s BR \qquad (2.2)$$

where

$\overline{e_n^2}$ = mean square value of the voltage

$k$ = Boltzmann's constant, $1.38 \times 10^{-23}$ joules per degree Kelvin

$T_s$ = temperature of the element (the source), $^{\circ}K$

$B$ = noise bandwidth of the element (to be defined later), cps

$R$ = resistive component of the element, ohms.

---

*Superscript numerals refer to references at end of report.

The noise power available is

$$N_a = kT_sB. \tag{2.3}$$

Therefore, there is available across the terminals of any resistive element a noise power of ($kT_s$) watts per cycle. This value establishes a minimum level for the input noise power density to any network.

b. Active source noise. The expression given above for the noise power available,

$$N_a = kT_sB, \tag{2.3}$$

is valid only for use with passive (resistive) sources. It is not used for active sources.

An active source may be considered in the same manner as an active network. The output noise power available from each may be described using the same expressions. The terminology may be changed, but the techniques are exactly the same.

C. NOISE BANDWIDTHS

1. EFFECTIVE NOISE BANDWIDTH. The "effective noise bandwidth" is an artificial property of the entire system. It refers to the numerical value of the bandwidth used with the input noise power density and the term describing the over-all system noise performance to compute the total noise power developed in the output. The total noise power in the output, in turn, sets the basic sensitivity of the system.*

$$\begin{bmatrix}\text{Total system}\\ \text{output noise}\\ \text{power}\end{bmatrix} = \begin{bmatrix}\text{Input noise}\\ \text{power}\\ \text{density}\end{bmatrix}\begin{bmatrix}\text{Over-all}\\ \text{system}\\ \text{gain}\end{bmatrix} B_{eff} + \begin{bmatrix}\text{Noise power}\\ \text{density at}\\ \text{output due}\\ \text{to excess}\\ \text{noise added}\\ \text{by system}\end{bmatrix} B_{eff} \tag{2.4}$$

*For further discussion of $B_{eff}$ see Section IX. B.3.C., p.

2. NOISE BANDWIDTH OF A NETWORK. When considering only one portion of a system that may consist of one or more stages, the bandwidth that is used in the various expressions for noise power is not necessarily equal to what is commonly termed the "3-db bandwidth of the response curve". The "noise bandwidth", B, is defined by the following expression:[32]

$$B \triangleq \frac{1}{G_0} \int_0^\infty G(f)\, df \,, \qquad (2.5)$$

where $G(f)$ = Available power gain at frequency f. The available gain of a network is "by definition independent of the impedance presented to the network by the output circuit, but is a function of the generator impedance".[63]

$G_0$ = Available gain at some convenient reference frequency, $f_0$, usually frequency of maximum response.

The physical significance of this integration and averaging is to determine a value for the noise bandwidth that can be applied to an equivalent rectangular bandpass with a constant gain $G_0$.

A table in Lawson and Uhlenbeck[36] gives the relationship between the noise bandwidth and the 3-db bandwidth for singly tuned circuits (1, 2, 3, and 4 stages), doubly tuned circuits (1 and 2 stages), triply tuned circuits (1 stage), quadruply tuned circuits (1 stage), and quintuply tuned circuits (1 stage). The figures for the singly tuned circuits are given below.[36] See Table II-1.

TABLE II-1 RATIO OF NOISE BANDWIDTH TO 3-db BANDWIDTH

| No of stages | 3-db bandwidth | Noise bandwidth B | Ratio B/b |
|---|---|---|---|
| 1 | 1 0* | 1 57 | 1.57 |
| 2 | 0 643 | 0 785 | 1 22 |
| 3 | 0 51 | 0.59 | 1 15 |
| 4 | 0 434 | 0 498 | 1 145 |

*By definition

The noise bandwidth of a circuit is often referred to as the effective bandwidth;[12,16] however, in this study the "effective noise bandwidth" will refer to that bandwidth used when computing the noise power output for the <u>entire system</u> and the "noise bandwidth" will refer to a <u>single</u> network.

3. SUMMARY ON NOISE BANDWIDTHS. The noise bandwidth of a network is obtained from the formula given above. Often this means that the response must be plotted and graphical integration methods used.[32] For networks composed of simple circuits B has been calculated. For complex networks it is often necessary to estimate B, keeping in mind that, for a network of many synchronously tuned stages, B is approximately equal to the 3-db bandwidth. The effective bandwidth of a system is a function of the bandwidths of the various stages in the system, but the derivation of this bandwidth depends on the type of system being considered as well as the relative noise performance of its various stages. In fact, an effective noise bandwidth for the system may not exist. The effective bandwidth will be covered in detail in Part Three of this report.

## D. NOISE POWER AND NOISE POWER DENSITY

There are two equally acceptable methods of referring to network noise power: "total noise power" and "noise power density". The use of "total power" is the most common, although serious problems can result if it is used indiscriminately. A much "safer" quantity to use is the noise power density; for, knowing the noise bandwidth of a network or the effective noise bandwidth of a system, one can easily calculate the total power. It should be noted, for those who may not be familiar with noise problems, that the noise being considered is assumed to be "white noise" in that its frequency spectrum, just as that of white light, is constant over the noise bandwidth.* When thermal noise is passed through any <u>linear</u> network this property is retained, although the amplitude of the spectrum as a whole may be changed.

*This statement is exactly true for thermal noise, and a good approximation for excess network noise over the passband of a narrowband network.

When there is any question as to what the "noise bandwidth" of a device is or what the "effective bandwidth" of the system is, the problem can be examined using noise power density expressions, and the output noise power can be calculated when the bandwidth is determined, if the "density" is constant over the entire bandwidth in question. If this is not the case, it will be necessary to divide the bandwidth into smaller segments, each having a constant output noise power density, and then to calculate the total noise power in the output as the sum of the power in each of the smaller incremental bandwidths. An example of this technique will be presented in Appendix C which considers a complex problem involving the image frequency response of a superheterodyne receiver.

Just as the total noise power may be multiplied by the power gain of a device, or be increased by the addition of excess noise power added by the device, so may the noise power density be multiplied by the gain, and increased by excess noise power densities. Extreme caution is warranted in either case if there is a situation involving different bandwidths.

## E. TEMPERATURE AND FREQUENCY CONSIDERATIONS IN NOISE PERFORMANCE

For nearly all active networks, the noise power added to the output by the network varies with the center frequency of the passband, even though the noise bandwidth remains constant. Therefore, it is an essential part of the description of the noise performance of a network to specify the center frequency considered. The gain of the network must also be given as well as the noise bandwidth.

The ambient temperature of the network may also affect the network noise performance. The excess noise added by the network may be a function of its ambient temperature, but this temperature dependence is usually not considered in systems engineering. The systems designer normally begins his calculations, given a value for the network excess noise that is a function only of the center frequency and the noise bandwidth. The only commonly encountered exception to this is the consideration of the noise performance of a passive network which is a direct function of the network ambient temperature.

## III. DESCRIBING NETWORK NOISE

### A. INTRODUCTION

1. NOISE FACTORS AND NOISE TEMPERATURES. With the present state of confusion in this field caused by a multiplicity of definitions, an engineer is in danger of creating more confusion as soon as he mentions "noise factors" or "noise temperatures". After some examination, though, what first appeared to be a completely illogical and unnecessary complication of the subject is found to have some semblance of order. One of the purposes of this paper is to point out the basic philosophy governing all of the methods of describing the "noisiness" of a network. It will not be possible to fully examine this topic and cover all of its aspects here, but an attempt will be made to correlate in one centralized development most of the important details. The purpose of this development is to acquaint the systems engineer with the many variations possible in the methods of referring to network noise, and to show how one may be converted to another. Two tables giving conversion factors and useful formulas summarize the results, whereas, in the text proper, the terms are defined and their use in equivalent block diagrams is illustrated.

There are two general methods employed to describe the noise performance of a network: noise factors (or figures), and noise temperatures. Only those terms in common use will be covered in detail. Some others that might possibly be used will be mentioned in the summary to this section.

To conclude this section, "source temperatures" of both signal and noise sources will be discussed.

2. EQUIVALENT BLOCK DIAGRAMS FOR LINEAR NETWORKS. It is possible to clarify greatly the calculations involved in determining the physical significance of the various noise factors and noise temperatures if each linear network is represented by a combination of an ideal noiseless network and an excess-noise generator, as in Fig. 3.1. The terminal characteristics of this combination must be the same as those for the actual network; therefore, the input signal power, input noise power, output signal power, and output noise power must all be equal, respectively, to those values obtained from the actual network.

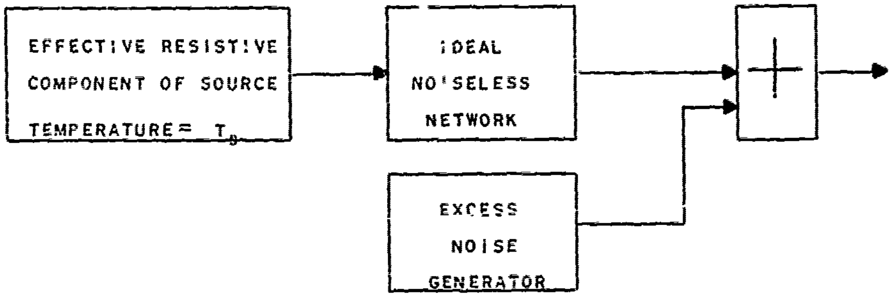



FIG. 3.1. Equivalent block diagram of a linear network.

There is no control over the input values; but the output noise power can be separated into two parts: amplified input noise, and excess noise generated in the network. It is then possible to refer the noise added by the network to the input or the output, and to describe it by different terms.

## B. THREE NOISE FACTORS

1. INTRODUCTION. After its introduction in 1942 by D. O. North, the noise factor came into widespread use as a method of describing the noise performance of a network. At the time of its introduction, engineers were just beginning to become interested in a quantitative measure of the "noisiness" of a system, for that date approximated the beginning of general interest in equipment that operated above 30 Mc. Prior to this time the level of static and other interference in the frequency ranges of importance was such that the noise performance of the receiver itself was not very significant in determining the over-all sensitivity of a system.

The "standard noise factor" was the term first defined, but it was apparent immediately that this term was inapplicable when the source temperature was not the standard. In his original work, North[47] also defined the "operating noise factor" which will be discussed below; and in 1948, Goldberg[15] introduced the "effective noise factor" which will also be covered here.

2. BASIC CONCEPT OF NOISE FACTORS. To compare the actual performance of a network to that of ideal devices, the terms noise factor and noise figure are commonly used. "The noise factor of an amplifier is the ratio of the actual output noise power available to that which would be available if the amplifier merely amplified the thermal noise of the source."[12,49] Or, if the input to this network is the output of another, the ideal device merely amplifies the output noise power of the source network.

The term "noise figure" is often used interchangeably with "noise factor", and common usage has become such that both often refer to either the db figure or the power ratio. The calculations in this paper will use primarily the power ratio. When the db figure is required, it will be specifically noted.

Although it is not implied by the definition given above, another one of the prime functions of any noise factor is to express the total noise power of a network by an expression similar to the one given below.

$$(\text{Total noise power output}) = \overline{F}\, kTBG \qquad (3.1)$$

Briefly, then, the two uses of noise factors are:

(1) to compare the noise performance of an actual network to that of an ideal noiseless device, and

(2) to express the <u>total</u> noise output of a network in a simple expression.

3. SPOT AND AVERAGE NOISE FACTORS. The excess noise power added by the network varies over the pass-band of the network. The value of the noise added at any given frequency may be a function of the gain of the network only, or it may be a function of both the frequency dependence of the gain and the frequency dependence of the noise generating process.

To emphasize this particular point the term "spot noise factor" is often used to refer to that value applicable for an incremental frequency band. It is then customary to use "average noise factor"* to refer to the ratio of the total available noise power output from the amplifier to the part of the total available noise power output which is due solely to the noise generated by the source.[32]

$$\overline{F} \triangleq \frac{\int_0^\infty F(f)\,G(f)\,df}{\int_0^\infty G(F)\,df} \qquad (3.2)$$

where $\overline{F}$ = the average noise factor

$F(f)$ = the spot noise factor at frequency f

$G(f)$ = available gain of the network at frequency f.

"The average noise factor is defined as the ratio of (1) the total noise power delivered into the output termination by the transducer, when the noise temperature of the input termination is standard (290°K) at all frequencies, to (2) that portion of (1) engendered by the input termination. For heterodyne systems, (2) includes only that portion of the noise from the input termination which appears in the output via the principal-frequency transformation of the system, and does not include spurious contributions such as those from an image-frequency transformation."[32]

Since all of the definitions of the noise factors given below will use total noise powers, the quantities actually defined are "average noise factors". The normalization is done in deriving the expression for the noise bandwidth. Also, the assumption is made that the frequency dependence of the noise generating process is negligible over the frequency range of interest.

The spot noise factor is used in the rigorous analysis of the noise performance of cascaded networks.**

---

*Also called the "integrated noise factor" by Lawson and Uhlenbeck.[36]

**See for example Freeman,[11] p. 194.

4. THE "STANDARD" NOISE FACTOR. As shown in Eq. (2.1), the total noise output of a network is a combination of excess noise, added by the network, and the amplified noise from the source. If the equivalent noise temperature of the source is equal to the standard temperature (normally taken to be 290°K), the "standard" noise factors may be used to compare the performance of the actual network to an "ideal noiseless" one.

The actual total output noise power is $N_0$, but the output noise power of an ideal network would be

$$\begin{pmatrix}\text{Amplified input}\\ \text{noise power}\end{pmatrix} = kT_0BG_0 \ . \tag{3.3}$$

Then the expression for the standard noise factor is

$$\overline{F} = \frac{N_0}{kT_0BG_0} \tag{3.4}$$

where
- $B$ = noise bandwidth of the network.
- $\overline{F}$ = "standard" noise factor.
- $G_0$ = maximum available power gain of the network.
- $k$ = Boltzmann's constant, $1.38 \times 10^{-23}$ joules per degree Kelvin.
- $N_0$ = total output noise power from network.
- $T_0$ = standard temperature, 290°K (in this formula, also the source temperature).

The definition given above for $(\overline{NF})_0$ may be rewritten as follows

$$\overline{F} = \frac{N_0}{G_0N_i} \quad (\text{for } T_s = T_0 \text{ only}) \tag{3.5}$$

where $N_i$ = network input noise power = $kT_0B$

The available power gain, $G_0$, may be defined by the following expression.

$$G_0 = \frac{S_0}{S_i} \ . \tag{3.6}$$

where $S_0$ = available output signal power

$S_i$ = available input signal power.

When this definition for $G_0$ is substituted into (3.5) another common definition of the noise factor is obtained:*

$$\overline{F} = \frac{(S_i/N_i)}{(S_0/N_0)} \quad (\text{for } T_s = T_0 \text{ \underline{only}}) \tag{3.7}$$

It should be noted that although this definition uses the signal-to-noise ratio, "the noise figure is not a measure of the excellence of the output signal-to-noise ratio, but merely a measure of the degradation suffered by the signal-to-noise ratio as the signal and noise pass through the network in question."**

Again examining Eq. (2.1), it is seen that it can be expressed in terms of the standard noise factor.

$$\begin{bmatrix}\text{Total output}\\ \text{noise power}\\ \text{of network}\end{bmatrix} = \begin{bmatrix}\text{Amplified input}\\ \text{noise power}\end{bmatrix} + \begin{bmatrix}\text{Excess noise}\\ \text{power added by}\\ \text{the network}\end{bmatrix} \tag{2.1}$$

$$N_0 = kT_0BG_0 + (\overline{F} - 1)\, kT_0BG_0 \tag{3.8}$$

Using the standard noise factor it is then possible to draw an equivalent block diagram (Fig. 3.2) in which $(\overline{F} - 1)$ is used in the expression for the power output of the excess noise generator.

Normally this measure of the noise performance of the system is called simply "the noise factor"; however, some author, such as Davenport and Root,[9] have used the terminology "standard noise factor" to emphasize the importance of the requirement that the source be at the standard temperature.

Only under very rare circumstances is the source temperature in any practical system equal to the standard. Variations in the source temperature require modifications to the noise factor which will be covered in the following sections.

---

*It is emphasized that this definition for $\overline{F}$ is valid only for $T_s = T_0$.

**Goldberg,[15] p. 1208.

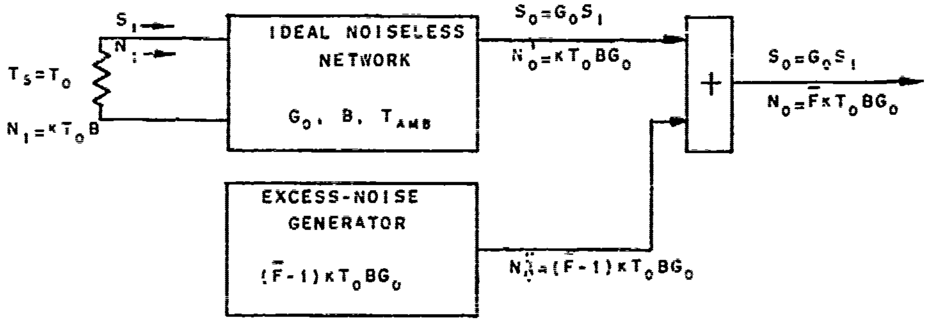



FIG. 3.2. Equivalent block diagram illustrating the use of the "standard" noise factor $\bar{F}$.

5. THE EFFECTIVE NOISE FACTOR. When the temperature of the source is different from the standard temperature, the standard noise factor can no longer be used in the expression for the total noise output of the network. The excess noise added by the network will remain the same, but the amplified input noise will change. In these circumstances then, a new noise factor must be defined.

The first noise factor that is defined for source temperature not equal to the standard is the "effective noise factor"

$$\bar{F}_s = \frac{N_0}{kT_sBG_0} \tag{3.9}$$

where $\bar{F}_s$ = the effective noise factor

$T_s$ = the source temperature.

In a manner similar to that of the preceding section, the definition for the effective noise factor may be written as follows:

$$\bar{F}_s = \frac{N_0}{G_0N_i} \quad \text{(for any } T_s\text{)} \tag{3.10}$$

Since this relation does apply, the same derivation as already given for $\bar{F}$ will result in the signal-to-noise-ratio definition of the effective noise factor.

$$\overline{F}_s = \frac{(S_i/N_i)}{(S_0/N_0)} \quad \text{(for } \underline{\text{any}}\ T_s\text{)} \tag{3.11}$$

Equation (2.1) may now be evaluated in terms of the effective noise factor

$$\begin{bmatrix}\text{Total output}\\ \text{noise power}\\ \text{of the network}\end{bmatrix} = \begin{bmatrix}\text{Amplified}\\ \text{input noise}\\ \text{power}\end{bmatrix} + \begin{bmatrix}\text{Excess noise power}\\ \text{added by the}\\ \text{network}\end{bmatrix} \tag{2.1}$$

$$N_0 = kT_sBG_0 + (\overline{F}_s - 1)\ kT_sBG_0 \tag{3.12}$$

Since the network excess noise remains constant under all conditions, it is very easy to establish the relationship between $\overline{F}$ and $\overline{F}_s$.

$$(\overline{F} - 1)\ kT_0BG_0 = (\overline{F}_s - 1)\ kT_sBG_0 \tag{3.13}$$

$$(\overline{F} - 1)\ T_0 = (\overline{F}_s - 1)\ T_s \tag{3.14}$$

It is important to note that the standard noise factor <u>always</u> has the same value since it is <u>defined</u> <u>only</u> for $T_s = T_0$, but the effective noise factor <u>varies</u> with the source temperature. Chart III-1* will permit quick conversion between the standard noise figure and the effective noise figure (both in db).

Using Eq. (3.12), it is possible to draw an equivalent block diagram for the network when $T_s \neq T_0$. See Fig. 3.3.

This noise factor was introduced by Goldberg[15] in 1948 and given the name "effective noise factor"** by Davenport and Root.[32]

---

*Reprinted from Oliver.[49]

**Note that this is very confusing, since "operating noise factor" normally refers to the term to be discussed next.

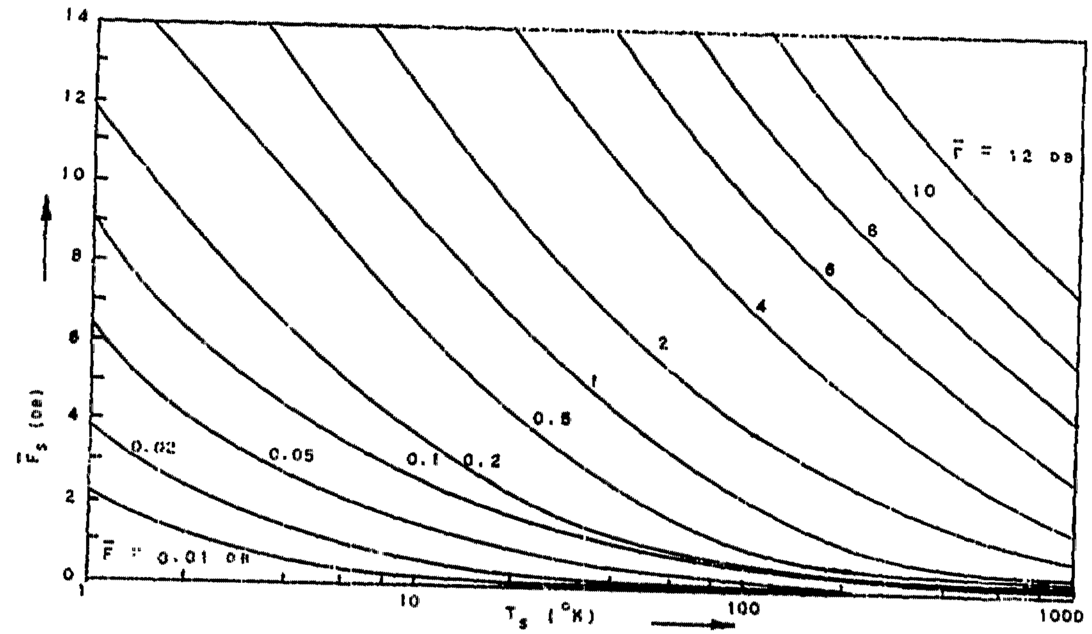



CHART III-1: Conversion chart for $\overline{F}_s$ and $\overline{F}$.

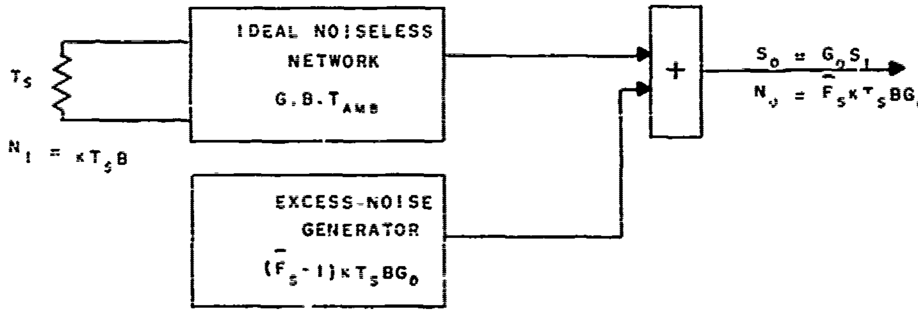



FIG. 3.3. Equivalent block diagram illustrating the use of the effective noise factor $\bar{F}_S$.

6. THE OPERATING NOISE FACTOR. The term originally introduced by D. O. North[47] in 1942, to use with the source at some temperature other than the standard, is the "operating noise factor". The operating noise factor is defined by the following equation

$$\bar{F}_{op} = \frac{N_0}{kT_0 BG_0} \qquad (3.15)$$

where $\bar{F}_{op}$ = the operating noise factor.

In this case the relation

$$\bar{F}_{op} = \frac{N_0}{G_0 N_i}$$

does not apply. Therefore,

$$\bar{F}_{op} \neq \frac{N_0}{G_0 N_i} \qquad (3.16)$$

Therefore the operating noise factor cannot be defined in terms of the signal-to-noise ratios.

$$\bar{F}_{op} \neq \frac{(S_i/N_i)}{(S_0/N_0)} \qquad (3.17)$$

Equation (2.1) may also be evaluated using the operating noise factor

$$\begin{bmatrix}\text{Total output}\\ \text{noise power}\\ \text{of the network}\end{bmatrix} = \begin{bmatrix}\text{Amplified}\\ \text{input noise}\\ \text{power}\end{bmatrix} + \begin{bmatrix}\text{Excess noise power}\\ \text{added by the}\\ \text{network}\end{bmatrix} \tag{2.1}$$

$$N_0 = kT_sBG_0 + (\overline{F}_{op}T_0 - T_s)\, kBG_0 \tag{3.18}$$

Equating the expressions for the excess network noise using $\overline{F}$ and $\overline{F}_{op}$, the following relation is obtained:

$$(\overline{F} - 1)\, T_0 = (\overline{F}_{op}T_0 - T_s) \tag{3.19}$$

$$\overline{F}_{op} = (\overline{F} - 1) + \frac{T_s}{T_0} \tag{3.20}$$

Or, using a term to be defined later,

$$\overline{F}_{op} = \overline{F} + \left(\frac{T_s - T_0}{T_0}\right) \tag{3.21}$$

where

$\left(\frac{T_s - T_0}{T_0}\right)$ = the relative excess noise temperature of the source

Chart III-2* will permit rapid conversion between the standard noise figure and the operating noise figure (both in db).

Using Eq. (3.18), it is possible to draw an equivalent block diagram for the network using $\overline{F}_{op}$. See Fig. 3.4.

This quantity was also called both the "modified noise factor" and the "effective noise factor" by Lawson and Uhlenbeck.

7. COMMENTS ON $\overline{F}_s$ AND $\overline{F}_{op}$. Using either of the modified noise factors defined above will produce correct results if the proper temperature is used in the expression for the total noise power output. The choice as to which one to use will depend on which of the two functions of the noise factor is most important in any given case.

*Reprinted from Strum.[61]

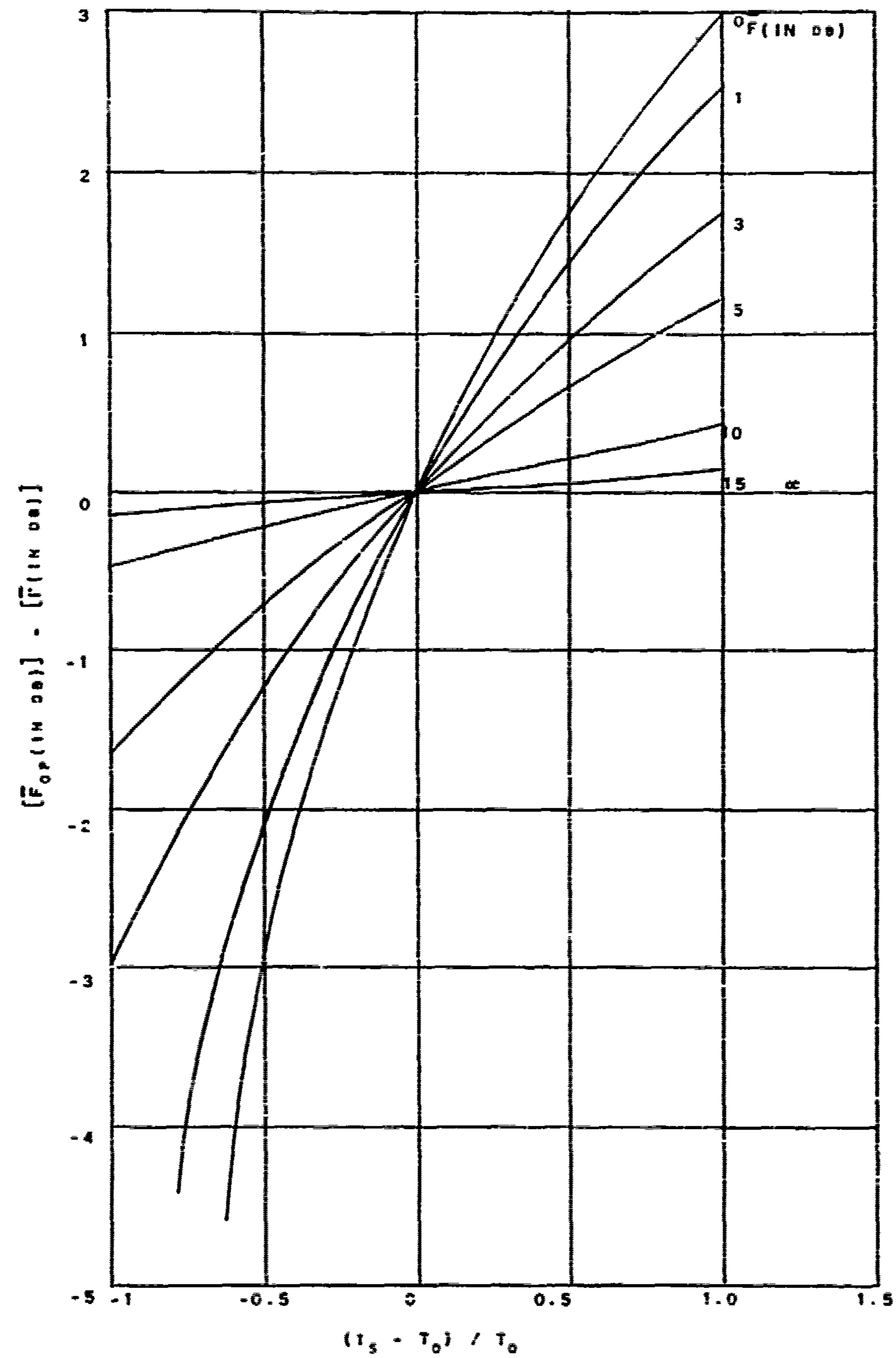



Chart III-2: Conversion chart for $\bar{F}_{op}$ and $\bar{F}$.

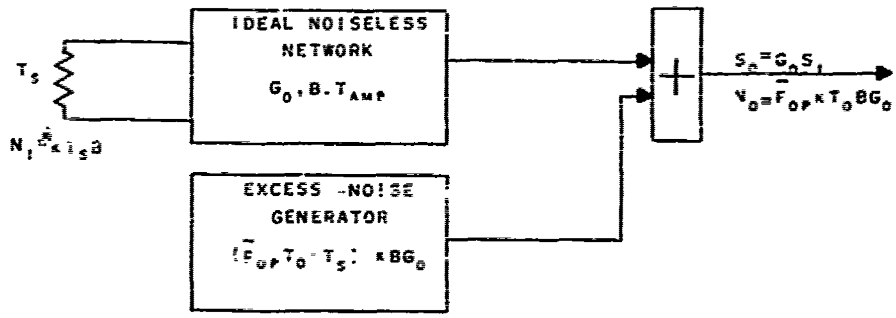



FIG. 3.4. Equivalent block diagram illustrating the use of the operating noise factor, $\overline{F}_{op}$

If it is desired to know how much more noise there is in the output of an actual network than in an ideal noiseless one, the effective noise factor, $\overline{F}_s$, must be used. The value of $\overline{F}_s$ gives the ratio between the output noise of the actual device and that of the ideal. This information then specifies how much the noise output can be reduced by improving the system. For this reason, the effective noise factor is perhaps the more appropriate one to use in comparing the noise performance of two different systems operating under the same conditions.

If it is desired to compare the noise performance of the same system operating under two different conditions of apparent source temperature, the operating noise factor, $\overline{F}_{op}$, should be used. When the source is at a temperature below the standard, the total noise power output will be lower by the difference in the amplified source noise. The signal output power will remain unchanged, so that the receiver will be able to detect a smaller signal. A lower value for the noise factor normally connotes better system sensitivity, but the following example presented by Peter Strum[61] will serve to illustrate the confusion that can arise.

Consider a receiver with a standard noise figure equal to 10 db. The source temperature, $T_s$, is $97.7^\circ K = (T_0/3)$. In this case then

$$\overline{F}_s = 14.7 \text{ db}$$

and

$$\overline{F}_{op} = 9.7 \text{ db}$$

This is a general characteristic of these two noise figures. They both will give the same results for the total noise power output, since the temperature used with $\overline{F}_s$ is only one-third of that used with $\overline{F}_{op}$. For receiver comparisons, then, it will be better to use the operating noise figure, since this will give the results normally expected---a lower noise figure for better sensitivity.

Although it is not generally recognized, the use of these different noise figures can cause more confusion than perhaps anything else. So often they are merely derived in part or defined broadly without making it clear what temperature must be used with each.[9,11] It is hoped that a knowledge of how the various quantities of interest are expressed in terms of each of the modified noise factors will alert the reader as to which one is being employed. (See Tables III-2 (b) and (c) in this section.)

## C. COMMON NOISE TEMPERATURES

1. INTRODUCTION. Although the three noise factors are completely adequate to describe all of the features of the noise associated with a network, there was a desire for other terms that would permit the use of shorter and simpler equations. The result was a group of terms commonly referred to as "noise temperatures". The confusion associated with this title is primarily a result of its indiscriminate use. Engineers working in various fields were interested in different aspects of the noise of a network or device, and the term used by each group was normally chosen so as to simplify the calculations that were most common in their work. The confusion arises when the terms used are not fully defined and all are referred to by the completely inadequate title "the noise temperature".

There are three decisions, each having two possible answers, that have to be made in choosing which "noise temperature" to use.

The quantity of interest may be either the total network output noise power or only that portion of the output noise power added by the network; it may be desired to refer this quantity to the input or to the output; and, finally, it may be more convenient to use a normalized temperature ratio than a temperature in degrees Kelvin. Such a systematic approach was not used when the individual terms were first derived, but the use of these three factors does permit an organized study of all of the terms that have been developed. Of the eight possible noise temperatures, only the four in common use will be covered in detail here.

It has become a common practice to refer to the generic group of terms that will be discussed below as "noise temperatures". The use of the term "temperature" may be misleading. Only in one case is the "temperature" something that can be measured physically, the source temperature. In the cases considered in this section, "noise temperature" might be described as a fictitious electronic quantity used only to refer to an apparent or equivalent temperature of a resistor that has a noise power output equal to some component of the noise power associated with the network. For several of the terms to be discussed, the quantity is dimensionless and merely represents a ratio of two "temperatures". This point will become clearer as the various terms are defined.

2. EQUIVALENT OUTPUT NOISE TEMPERATURE. If the quantity of interest is the total noise output of the network, it is desirable to be able to express this quantity as simply as possible. In order to do this the "equivalent output noise temperature" is used. Then the total output noise power is given by

$$N_O = T_{eq}B \tag{3.22}$$

where

$T_{eq}$ = the equivalent output noise temperature.

It was shown earlier that the total output noise power of the network can also be evaluated by using noise factor. For <u>any</u> source temperature the total output noise is given by

$$N_O = \overline{F}_{op}kT_OBG_O \tag{3.23}$$

or

$$N_0 = \overline{F}_s k T_s B G_0 \tag{3.24}$$

Therefore*

$$T_{eq} = \overline{F}_{op} T_0 G_0 \tag{3.25}$$

(For any $T_s$)

$$T_{eq} = \overline{F}_s T_s G_0 \tag{3.26}$$

for <u>any</u> source temperature.

If the source is at the standard temperature, then the standard noise factor may also be used.

$$T_{eq} = \overline{F}\, T_0 G_0 \qquad \text{(For } T_s = T_0\text{)} \tag{3.27}$$

The physical significance of the equivalent output noise temperature is that the entire noise power output of the network can be visualized as coming from a resistive component at the output which is at the temperature $T_{eq}$. See Fig. 3.5. Note that even though the source is at $T_s$ the input noise power is assumed to be zero and the entire output noise power comes from the resistor at the temperature $T_{eq}$.

The use of the equivalent output noise temperature permits the use of very simple expressions when examining the total noise power output at the output terminals.

This temperature is also called the "effective noise temperature" by Davenport and Root[9] and care should be taken not to confuse it with another term to be defined later.

3. NOISE TEMPERATURE RATIO. It is easier to perform calculations with small numbers. Therefore, if the equivalent output noise temperature is very large, it can be normalized by dividing it by the standard temperature. It is then possible to express the total noise output of the network, using the "noise temperature ratio", $t_r$,

$$N_0 = k t_r T_0 B \tag{3.28}$$

*Since $\overline{F}_{op}$ and $\overline{F}_s$ are both functions of the source temperature, $T_{eq}$ will also vary with $T_s$ to take into consideration the variations in the amount of amplified input noise.

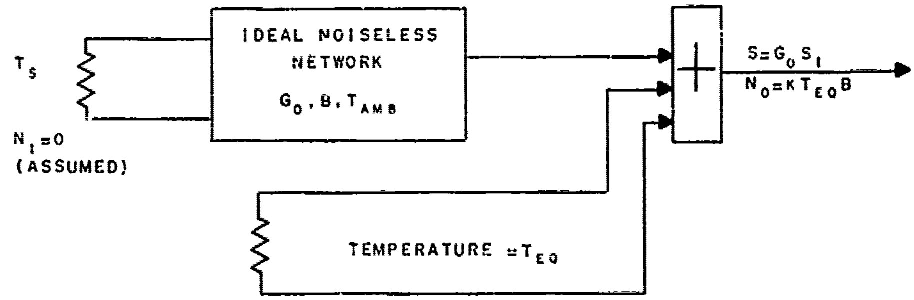



FIG. 3.5. Equivalent block diagram illustrating the physical significance of the equivalent output noise temperature $T_{eq}$.

Therefore, from Eqs. (3.25) and (3.26) it can be seen that for <u>any</u> source temperature,

$$t_r = \overline{F}_{op} G_0 \tag{3.29}$$

or (For any $T_s$)

$$t_r = \overline{F}_s \left( \frac{T_s}{T_0} \right) G_0 \tag{3.30}$$

<u>Only for the source at the standard temperature</u> does

$$t_r = \overline{F}\, G_0 \qquad \text{(For } T_s = T_0\text{)} \tag{3.31}$$

The requirement that $T_s = T_0$ is usually assumed when the noise temperature ratio is defined, but only rarely is this condition specified. Using this assumption, then, and the expression for the noise temperature ratio in terms of the standard noise factor, the most common use of the ratio will be illustrated.

A common configuration of radar receivers is a crystal mixer followed by an intermediate-frequency amplifier. The standard noise factor of the combination of two cascaded networks will be shown later to be

$$\overline{F}_{12} = \overline{F}_1 + \frac{\overline{F}_2 - 1}{G_{0_1}} \tag{3.32}$$

Then the standard noise factor of the crystal mixer/i-f amplifier combination could be given by

$$\overline{F}_{M-IF} = \frac{t_{r_m} + \overline{F}_{IF} - 1}{G_{0_M}} \tag{3.33}$$

or

$$\overline{F}_{M-IF} = L_M(t_{r_M} + \overline{F}_{IF} - 1) \tag{3.34}$$

where

$\overline{F}_{IF}$ = "standard" noise factor of the i-f amplifier,

$\overline{F}_{M-IF}$ = "standard" noise factor of the crystal i-f amplifier combination,

$G_{0_M}$ = maximum available conversion gain of the crystal mixer,

$L_M$ = conversion loss of the crystal mixer ($1/G_{0_M}$),

$t_{r_M}$ = noise temperature ratio of the crystal.

Historically, the use of the noise temperature ratio to describe the performance of a crystal mixer was probably the first use of any noise temperature. This term was used very often in early radar work, and Van Voorhis[66] refers to it simply as the "crystal temperature ratio", Ginzton[14] called it the "crystal noise temperature", and Pritchard[53] referred to it as the "mixer noise ratio".

It would be possible to illustrate the physical significance of the noise temperature ratio in general by drawing an equivalent block diagram exactly similar to Fig. 3.5 except that the temperature of the resistor would be $t_r T_0$. It is also possible to describe the output of an excess noise generator, using the noise temperature ratio. See Fig. 3.6.

The noise temperature ratio is also referred to as the "relative noise temperature" by Davenport and Root.[9]

4. EFFECTIVE INPUT NOISE TEMPERATURE.* In the field of radio

*This term is defined in an IRE standard.[32] This use of this term is becoming more common and will perhaps be the most important "temperature" in the future.

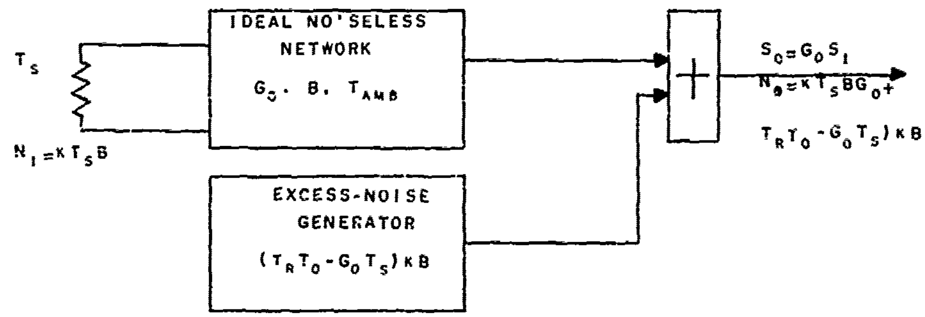



FIG. 3.6. Equivalent block diagram illustrating the use of the noise temperature ratio $t_r$.

astronomy one item of prime importance is the ability of the receiving equipment to detect a change in the apparent "temperature" of the source. For this reason, the additional noise <u>added</u> by the network is often referred back to the input terminals by the use of the "effective input noise temperature".*

$$\begin{bmatrix}\text{Total output noise}\\ \text{power of network}\end{bmatrix} = \begin{bmatrix}\text{Amplified input}\\ \text{noise power}\end{bmatrix} + \begin{bmatrix}\text{Excess noise power}\\ \text{added by network}\end{bmatrix} \quad (2.1)$$

$$N_0 = kT_sBG_0 + kT_{eff}BG_0 \quad (3.35)$$

$$T_{eff} \triangleq \frac{N_0}{kBG_0} - T_s \quad (3.36)$$

---

*Since it is easier to compute with small numbers it may be desired to normalize this temperature as below:

$$t_{eff} \triangleq \frac{T_{eff}}{T_0}$$

where $T_{eff}$ = "effective input noise temperature <u>ratio</u>".

In somewhat the same way that the "equivalent output noise temperature" describes the total output noise referred to the output terminals, the "effective input noise temperature", as defined above, describes the noise added by the network referred to the input terminals.

This term is very useful when examining the excess network noise referred to the input terminals and results in very simple expression when so used.

The physical significance of this "noise temperature" is best illustrated by a series of three block diagrams in which the excess noise is first transformed to the input and then the two noise sources are combined so that the network effectively sees one source at an apparent temperature equal to the "source temperature" plus the "effective input noise temperature". See Fig. 3.7.

From these block diagrams it can be seen that the "effective input noise temperature" is also useful for dealing with problems where the source is at some temperature other than the standard.

The complete title for this temperature has not been in use very long and some of the recent literature refers to it as the "effective noise temperature".[17] Because it refers to noise added by the receiver, this temperature is called the "receiver noise temperature" by Pawsey and Bracewell;[50] but in view of the great number of "temperatures" that are used in referring to receiver noise, it appears that this nomenclature is not specific enough for common use.

5. EXCESS NOISE TEMPERATURE RATIO. Another term that is often used in describing the noise characteristics of crystals is the "excess noise temperature ratio". From the definiation of the equivalent output noise temperature the following relation holds under all conditions

$$N_0 = kT_{eq}B \tag{3.37}$$

However, a certain amount of the output noise power merely represents amplified input noise.

$$(\text{Amplified input noise power}) = kT_s BG_0 \tag{3.38}$$

Then a new term can be defined as the "excess noise temperature ratio", $t_{ex}$, so that

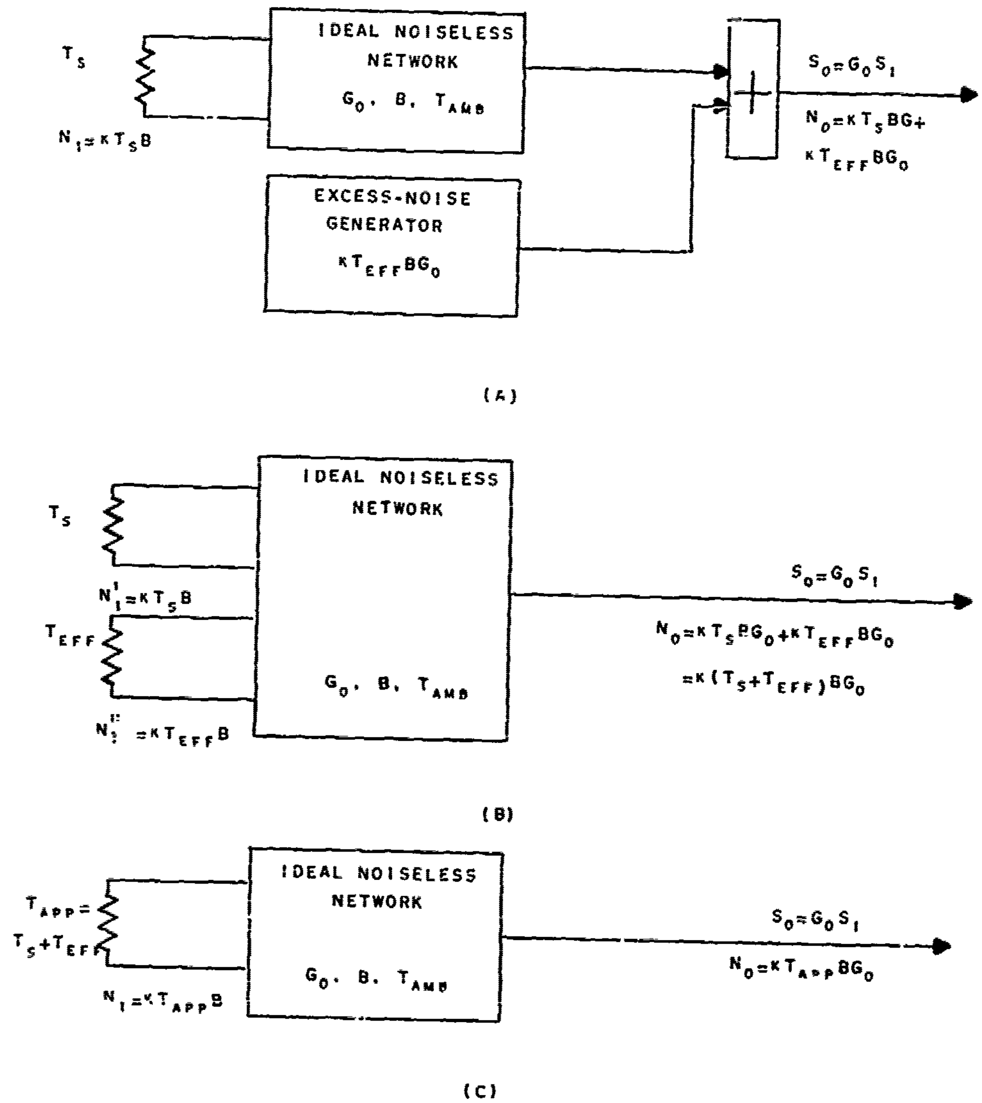



FIG. 3.7. Series of equivalent block diagrams illustrating the physical significance of the effective input noise temperature $T_{eff}$.

$$N_0 = kT_sBG_0 + kt_{ex}T_0B \qquad (3.39)$$

$$t_{ex} \triangleq \frac{N_0}{kT_0B} - \frac{G_0T_s}{T_0} \qquad (3.40)$$

where $t_{ex}$ = excess noise temperature ratio. The excess noise temperature ratio is a normalized measure of the excess noise generated in the device, referred to the output.

The equivalent block diagram shows that the "excess noise temperature ratio" simplifies the expression for the output of the excess noise generator. See Fig. 3.8.

There have not been any other names encountered for this term.

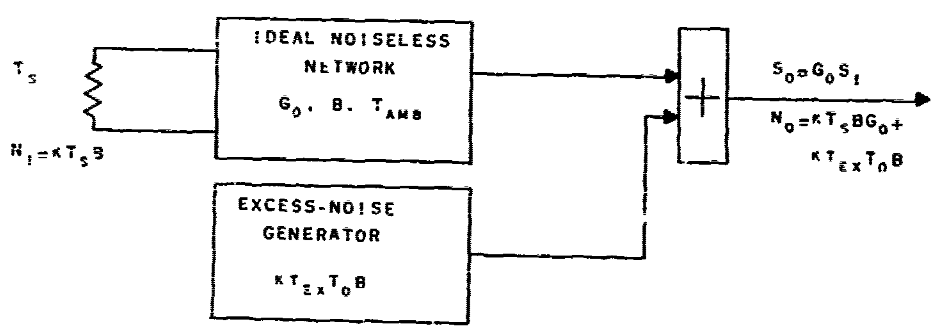



FIG. 3.8. Equivalent block diagram illustrating the use of the excess noise temperature ratio $t_{ex}$.

## D. SUMMARY ON NOISE FACTORS AND NOISE TEMPERATURES

1. INTRODUCTION. The use of the many "noise temperatures" to describe virtually the same thing may seem quite unnecessarily confusing. This is certainly true; however, different "temperatures" have been accepted for use in different types of networks; and the purpose of this section has been to show how the various quantities are defined, and their physical significance. Now all that remains to be done is to show the equivalence of one term to another.

For any given source temperature the <u>total</u> output noise power is fixed, and under all conditions of source temperature the excess noise power added by the network is approximately the same. Using these two facts, it is possible to derive the equations relating one descriptive term to another. These conversion equations are all given in Table III-1.

Table III-2 gives expressions for certain properties of the noise in terms of the different "temperatures". Although it was not mentioned specifically in this section, noise power density has certainly been implied in all the expressions for power, since each of these contained the noise bandwidth of the network. It is often easier to consider the power density instead of the total power, as will be seen in some of the later work. In fact the use of the power density for the noise, instead of the total power, is often the only way that certain problems can be solved. The second table considers not only power but also power density.

After examining the forms of the expressions in the second table, it is easy to see why the various methods of calculating and referring to noise have arisen. Anyone who is particularly interested in one technique of examining noise, whether it be total power or power density, and referred to the input or to the output, can find a "temperature" for describing this "noise" that will greatly simplify his equations. Because all these methods are used, the systems engineer must be familiar with all of them and be able to quickly convert from one to another.

2. TABLES. Given the following characteristics of the network:

$B =$ noise bandwidth

$G_0 =$ maximum available gain

TABLE III-1. CONVERSION FORMULAS

| | Given / To get | Definition | $\overline{F}$ | $\overline{F}_e$ | $\overline{F}_{op}$ | $T_{eq}$ | $t_r$ | $T_{eff}$ | $t_{ex}$ |
|---|---|---|---|---|---|---|---|---|---|
| $\overline{F}$ | Noise factor ("Standard") | $\frac{N_o}{kT_oBG_o}$ $(T_s=T_o)$ | — | $(\overline{F}_e-1)\frac{T_s}{T_o}+1$ | $\overline{F}_{op}+1-\frac{T_s}{T_o}$ | $\frac{T_{eq}}{G_oT_o}-\frac{T_s}{T_o}+1$ | $\frac{t_r}{G_o}-\frac{T_s}{T_o}+1$ | $\frac{T_{eff}}{T_o}+1$ | $\frac{t_{ex}}{G_o}+1$ |
| $\overline{F}_e$ | Effective noise factor | $\frac{N_o}{kT_sBG_o}$ | $(\overline{F}-1)\frac{T_o}{T_s}+1$ | — | $\frac{\overline{F}_{op}T_o}{T_s}$ | $\frac{T_{eq}}{G_oT_s}$ | $\frac{t_rT_o}{G_oT_s}$ | $\frac{T_{eff}}{T_s}+1$ | $\frac{t_{ex}T_o}{G_oT_s}+1$ |
| $\overline{F}_{op}$ | Operating noise factor | $\frac{N_o}{kT_oBG_o}$ | $(\overline{F}-1)+\frac{T_s}{T_o}$ | $\frac{\overline{F}_eT_s}{T_o}$ | — | $\frac{T_{eq}}{G_oT_o}$ | $\frac{t_r}{G_o}$ | $\frac{T_{eff}}{T_o}+\frac{T_s}{T_o}$ | $\frac{t_{ex}}{G_o}+\frac{T_s}{T_o}$ |
| $T_{eq}$ | Equivalent output noise temperature | $\frac{N_o}{kB}$ | $(\overline{F}-1)G_oT_o+G_oT_s$ | $\overline{F}_eG_oT_s$ | $\overline{F}_{op}G_oT_o$ | — | $t_rT_o$ | $(T_{eff}+T_s)G_o$ | $t_{ex}T_o+G_oT_s$ |
| $t_r$ | Noise temperature ratio | $\frac{N_o}{kT_oB}$ | $(\overline{F}-1)G_o+\frac{G_oT_s}{T_o}$ | $\frac{\overline{F}_eG_oT_s}{T_o}$ | $\overline{F}_{op}G_o$ | $\frac{T_{eq}}{T_o}$ | — | $\frac{(T_{eff}+T_s)}{T_o}G_o$ | $t_{ex}+\frac{G_oT_s}{T_o}$ |
| $T_{eff}$ | Effective input noise temperature | $\frac{N_o}{kBG_o}-T_s$ | $(\overline{F}-1)T_o$ | $(\overline{F}_e-1)T_s$ | $\overline{F}_{op}T_o-T_s$ | $\frac{T_{eq}}{G_o}-T_s$ | $\frac{t_rT_o}{G_o}-T_s$ | — | $\frac{t_{ex}T_o}{G_o}$ |
| $t_{ex}$ | Excess noise temperature ratio | $\frac{N_o}{kT_oB}-\frac{G_oT_s}{T_o}$ | $(\overline{F}-1)G_o$ | $(\overline{F}_e-1)\frac{G_oT_s}{T_o}$ | $\left(\overline{F}_{op}-\frac{T_s}{T_o}\right)G_o$ | $\frac{T_{eq}}{T_o}-\frac{G_oT_s}{T_o}$ | $t_r-\frac{G_oT_s}{T_o}$ | $\frac{T_{eff}G_o}{T_o}$ | — |

## TABLE III-2(a). GENERAL NOISE FORMULAS

| | (Network total noise power output) | | (Amplified input noise power) | | (Excess noise power added by the network) |
|---|---|---|---|---|---|
| Using $\bar{F}$: | $N_o$ | = | $kT_oBG_o$ | + | $(\bar{F} - 1)\ kT_oBG_o$ |
| Using $\bar{F}_s$: | $N_o$ | = | $kT_sBG_o$ | + | $(\bar{F}_s - 1)\ kT_sBG_o$ |
| Using $\bar{F}_{op}$: | $N_o$ | = | $kT_sBG_o$ | + | $(\bar{F}_{op}T_o - T_s)\ kBG_o$ |
| Using $T_{eq}$: | $N_o$ | = | $kT_sBG_o$ | + | $k(T_{eq} - G_oT_s)\ B$ |
| Using $t_r$: | $N_o$ | = | $kT_sBG_o$ | + | $k(t_rT_o - G_oT_s)\ B$ |
| Using $T_{eff}$: | $N_o$ | = | $kT_sBG_o$ | + | $kT_{eff}BG_o$ |
| Using $t_{ex}$: | $N_o$ | = | $kT_sBG_o$ | + | $kt_{ex}T_oB$ |

TABLE III-2(b) NOISE POWER FORMULAS

| To get \ Given | $\bar{F}$ | $F_s$ | $\bar{F}_{op}$ | $T_{eq}$ | $t_r$ | $T_{eff}$ | $t_{ex}$ |
|---|---|---|---|---|---|---|---|
| Input (source) noise power referred to input | $kT_oB$ * | $kT_sB$ | $kT_sB$ | $kT_sB$ | $kT_sB$ | $kT_sB$ | $kT_sB$ |
| Output noise power due to amplified input noise referred to output | $kT_oBG_o$ * | $kT_sBG_o$ | $kT_sBG_o$ | $kT_sBG_o$ | $kT_sBG_o$ | $kT_sBG_o$ | $kT_sBG_o$ |
| Total output noise power referred to output | $\bar{F}kT_oBG_o$ | $F_s kT_sBG_o$ | $\bar{F}_{op}kT_oBG_o$ | $kT_{eq}B$ | $kt_rT_oB$ | $k(T_{eff}+T_s)BG_o$ | $k(t_{ex}T_o+G_oT_s)B$ |
| Total output noise power referred to input | $\bar{F}kT_oB$ * | $F_s kT_sB$ | $\bar{F}_{op}kT_oB$ | $\frac{kT_{eq}B}{G_o}$ | $\frac{kt_rT_oB}{G_o}$ | $k(T_{eff}+T_s)B$ | $\frac{k(t_{ex}T_o+G_oT_s)B}{G_o}$ |
| Output noise power due to excess network noise referred to output | $(\bar{F}-1)kT_oBG_o$ | $(F_s-1)kT_sBG_o$ | $(\bar{F}_{op}T_o-T_s)kBG_o$ | $k(T_{eq}-G_oT_s)B$ | $k(t_rT_o-G_oT_s)B$ | $kT_{eff}BG_o$ | $kt_{ex}T_oB$ |
| Output noise power due to excess network noise referred to input | $(\bar{F}-1)kT_oB$ | $(F_s-1)kT_sB$ | $(\bar{F}_{op}T_o-T_s)kB$ | $\frac{k(T_{eq}-G_oT_s)B}{G_o}$ | $\frac{k(t_rT_o-G_oT_s)B}{G_o}$ | $kT_{eff}B$ | $\frac{kt_{ex}T_oB}{G_o}$ |

*Valid only for $T_s = T_o$

TABLE III-2(c). NOISE POWER DENSITY FORMULAS

| To get \ Given | $\bar{F}$ | $\bar{F}_e$ | $\bar{F}_{op}$ | $T_{eq}$ | $t_r$ | $T_{eff}$ | $t_{ex}$ |
|---|---|---|---|---|---|---|---|
| Input noise power density referred to input | $kT_o$ * | $kT_a$ | $kT_a$ | $kT_a$ | $kT_a$ | $kT_a$ | $kT_a$ |
| Output noise power density due to amplified input noise referred to output | $kT_oG_a$ * | $kT_aG_a$ | $kT_aG_a$ | $kT_aG_a$ | $kT_aG_a$ | $kT_aG_a$ | $kT_aG_a$ |
| Total output noise power density referred to output | $\bar{F}kT_oG_a$ * | $\bar{F}_ekT_aG_a$ | $\bar{F}_{op}kT_aG_a$ | $kT_{eq}$ | $kt_rT_o$ | $k(T_{eff}+T_a)G_a$ | $k(t_{ex}T_o+G_aT_a)$ |
| Total output noise power density referred to input | $\bar{F}kT_o$ * | $\bar{F}_ekT_a$ | $\bar{F}_{op}kT_a$ | $\frac{kT_{eq}}{G_a}$ | $\frac{kt_rT_o}{G_a}$ | $k(T_{eff}+T_a)$ | $\frac{k(t_{ex}T_o+G_aT_a)}{G_a}$ |
| Output noise power density due to excess network noise referred to output | $(\bar{F}-1)kT_oG_a$ | $(\bar{F}_e-1)kT_aG_a$ | $(\bar{F}_{op}T_o-T_a)kG_a$ | $k(T_{eq}-G_aT_a)$ | $k(t_rT_o-G_aT_a)$ | $kT_{eff}G_a$ | $kt_{ex}T_o$ |
| Output noise power density due to excess network noise referred to input | $(\bar{F}-1)kT_o$ | $(\bar{F}_e-1)kT_a$ | $(\bar{F}_{op}T_o-T_a)k$ | $\frac{k(T_{eq}-G_aT_a)}{G_a}$ | $\frac{k(t_rT_o-G_aT_a)}{G_a}$ | $kT_{eff}$ | $\frac{kt_{ex}T_o}{G_a}$ |

*Valid only for $T_a = T_o$

$N_0$ = total output noise power

$T_0$ = standard temperature

$T_s$ = source temperature

The first table is constructed to enable the engineer to convert from one of the seven terms discussed to any other one. There may be other equations possible, but these are probably as simple as any. The definitions have been chosen expressly to remove any problems of having a source at a temperature other than the standard.* Many of the definitions given in the literature are not very exact on this point.

There is one definition that applies only for $T_s = T_0$---the definition of the "standard" noise factor. All of the conversion formulas apply for any source temperature, but it should be noted that many of the expressions given reduce greatly when $T_s = T_0$.

The second table is presented primarily to show that there is some basis for the multiplicity of "temperatures" that have developed. The simple forms obtained for the various quantities are easily discernible, and an engineer interested in referring to all noise in one particular manner can quickly choose the proper "temperature" to use to make his calculations the easiest. The second table also provides a ready reference for the engineer who is working systems-noise problems, although there will usually be more than one way of expressing many of the quantities. Note that there are four expressions in parts (b) and (c) of the second table that require that the source be at the standard temperature.

---

*Note that none of the signal-to-noise ratios have been used for the noise factors.

$$\overline{F} = \frac{(S_i/N_i)}{(S_0/N_0)}$$

$$\overline{F}_s = \frac{(S_i/N_i)}{(S_0/N_0)}$$

$$\overline{F}_{op} = \frac{(S_i/N_i)}{(S_0/N_0)}$$

3. OTHER POSSIBLE NOISE TEMPERATURES AND NOISE FACTORS.

a. Noise temperatures. After reading this section, the engineer may well believe that there could not possibly be any other "noise temperatures": any that have not been covered here. A little reflection on the subject will prove this not to be the case. The four temperatures which were discussed above are only those that have been found in common use. There are others possible; but their use, if any, is not sufficiently common to warrant going into great detail in their description. Furthermore, if any new terms are encountered, the engineer should be able, with the aid of the material in this section, to derive the physical significance of each "temperature" on his own.

In addition to other possible noise factors, there are eight possible noise temperatures.* The quantity of interest may be either the total network output noise or the excess noise added by the network. It may be desired to refer the quantity of interest to either the input or the output, and finally it may be advantageous to use either an absolute temperature in degrees Kelvin or a temperature ratio normalized by the standard temperature, $290^{\circ}K$. In all calculations preceding, the final one to compute---the over-all system sensitivity, the quantity of interest---is normally the network excess noise; and whether it is referred to the output or the input is largely a matter of choice, although for working with networks in cascade it is simpler to refer it to the input. The choice of using an absolute temperature or a ratio is usually made so that the resulting numbers of interest are small and as near unity as possible. For example, if $T = 10^{\circ}K$ it would be better to use the absolute temperature than the ratio $t = 0.03448$.

Table III-3 gives all eight possible noise temperatures. Those covered in the text earlier are outlined in heavy borders. As was mentioned above, four of the temperatures in the chart are not in common use and the symbols and titles are those of this author.

---

*There might be twelve different temperatures possible, if those referring to total system noise are defined separately for standard temperature sources and other temperature sources. Those temperatures referring to excess noise are not a function of the source temperature. Having different definitions for $t_r$ and $t_{r_s}$, for example, appears unnecessarily complicated.

TABLE III-3. THE EIGHT POSSIBLE NOISE TEMPERATURES

| | Total Network Output Noise | | Excess Noise Added by Network | |
|---|---|---|---|---|
| | Absolute temperature degrees Kelvin | Ratio, normalized to $T_o$ | Absolute temperature, degrees Kelvin | Ratio, normalized to $T_o$ |
| Referred to the input | $T_{in}$ Equivalent input noise temperature | $t_{in}$ Equivalent input noise temperature ratio | $\boxed{T_{eff}}$ Effective input noise temperature | $t_{eff}$ Effective input noise temperature ratio |
| Referred to the output | $\boxed{T_{eq}}$ Equivalent output noise temperature | $\boxed{t_r}$ Noise temperature ratio | $T_{ex}$ Excess noise temperature | $\boxed{t_{ex}}$ Excess noise temperature ratio |

b. Noise factors. The only difference among the three noise factors given above is the reference temperature used in calculating the total noise output of the network. There are, in fact, only two basically different noise factors, for the "standard noise factor" is a special case of both the "effective noise factor" and the "operating noise factor" for $T_S = T_0$. All of the noise factors given may be classed as terms referred to the network input, since the network gain, $G_0$, must be included in the expressions for the network output noise.

There are several variations of the noise factors that are possible, referring them to either the output or the input, or considering only the excess noise added by the network; but the complete coverage of all of these variations by the noise temperatures precludes the need for increasing the number of noise factors. The only additional term that might be of value is an excess "standard" noise factor that considers only the network excess noise.

$$F^* = (F - 1) \tag{3.41}$$

where $F^*$ = excess noise factor.

The usefulness of this term can be illustrated by examining the expression for the over-all system noise factor of 6 networks in cascade. Using the presently available notation this is given by the following equation:

$$F_{1-6} = F_1 + \frac{(F_2-1)}{G_{0_1}} + \frac{(F_3-1)}{G_{0_1}G_{0_2}} + \frac{(F_4-1)}{G_{0_1}G_{0_2}G_{0_3}} + \frac{(F_5-1)}{G_{0_1}G_{0_2}G_{0_3}G_{0_4}} + \frac{(F_6-1)}{G_{0_1}G_{0_2}G_{0_3}G_{0_4}G_{0_5}} \tag{3.42}$$

If the modified standard noise factor, $F^*$, were used, the expression would be much simpler:

$$F_{1-6} = F_1 + \frac{F_2^*}{G_{0_1}} + \frac{F_3^*}{G_{0_1}G_{0_2}} + \frac{F_4^*}{G_{0_1}G_{0_2}G_{0_3}} + \frac{F_5^*}{G_{0_1}G_{0_2}G_{0_3}G_{0_4}} + \frac{F_6^*}{G_{0_1}G_{0_2}G_{0_3}G_{0_4}G_{0_5}} \tag{3.43}$$

or

$$F^*_{1-6} = F^*_1 + \frac{F^*_2}{G_{0_1}} + \frac{F^*_3}{G_{0_1}G_{0_2}} + \frac{F^*_4}{G_{0_1}G_{0_2}G_{0_3}} + \frac{F^*_5}{G_{0_1}G_{0_2}G_{0_3}G_{0_4}} + \frac{F^*_6}{G_{0_1}G_{0_2}G_{0_3}G_{0_4}G_{0_5}} \cdots\cdots \tag{3.44}$$

The "average excess noise factor" would be the same as the "effective input noise temperature ratio". Note that in all cases

$$\left.\begin{aligned} \overline{F^*} &= \frac{T_{eff}}{T_0} \qquad (3.45) \\ \overline{F^*} &= t_{eff} \qquad (3.46) \end{aligned}\right\} \text{(For any } T_s\text{)}$$

E. SOURCE TEMPERATURES

1. NOISE SOURCE TEMPERATURES.[58] Thus far the "noise temperatures" considered have been defined by examining the network total output noise power, or that part of it added by the network. Somewhat analogous techniques can be used to examine the input noise power obtained from a noise source. These "temperatures" are of interest when using noise sources to measure the noise performance of networks.[58] The definitions for several of the useful terms will be given below; however, no further use of these "temperatures" will be made in this study.

$T_s \triangleq$ Noise source discharge temperature

$T_s - T_0 \triangleq$ Excess noise temperature of the noise source

$\frac{T_s}{T_0} \triangleq$ Relative noise temperature ratio of the noise source

$\left(\frac{T_s - T_0}{T_0}\right) \triangleq$ Relative excess noise temperature ratio of the noise source

$(T_s/T_0)$ is also equal to the ratio of the power per cycle, available from the noise source, to that available from a source at the standard temperature, $T_0$.

2. SIGNAL SOURCE TEMPERATURE - ANTENNAS. Although the apparent noise temperature of the source that is connected to the network does not describe any of the properties of the network itself, it is certainly of great importance in making any calculations involving system noise. Normally, the source is considered as being at the same ambient temperature as the equipment, which is often assumed to be the standard temperature, $290^{\circ}K$. If the source is an antenna pointed at the sky, as it may well be in a radar receiving system, the temperature of the source will probably differ quite greatly from the standard temperature.

An antenna system can be described by an equivalent circuit[16] as in Fig. 3.9. The reactive component of the antenna impedance will not have any effect on the noise power available to the receiver, but the two resistive components will. The ohmic resistance will be at the ambient temperature of the equipment and will contribute an amount of noise power based on this temperature; however, the "temperature" of the radiation resistance will be determined by the "temperature" of the objects at which the beam of the antenna is directed. In all likelihood the ohmic resistance will be very small compared with the radiation resistance, so that the antenna will generate little thermal-noise power. The primary problem is determining the equivalent temperature of the radiation resistance. It is normally necessary to obtain this temperature experimentally for the various frequencies of interest and the directions in which the antenna beam will be aimed. It can be defined by an integral equation; however, this equation has little application in finding actual values for the equivalent antenna temperature. "It should be noted that a radiation resistance is not a real resistance, and thus introduces no noise into the receiver except to the extent that it absorbs noise radiation from its surroundings."[48]

There are several methods that might be used in making noise calculations with a source temperature other than the standard. One such method was illustrated in the preceding section, using the effective input noise temperature of the network. See Fig. 3.7. Another method that might be employed is the use of an external noise factor.[48]

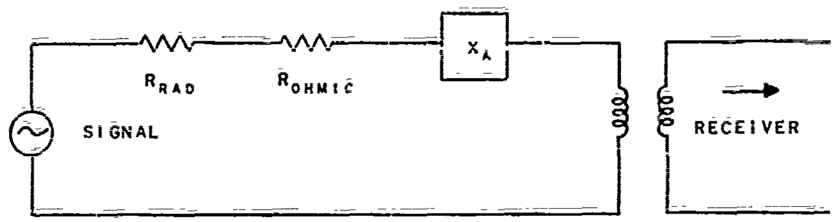



FIG. 3.9. Equivalent circuit of an antenna with losses.

The external noise factor is defined so that it is equal to unity when the average noise power density available from the antenna is the same as that available from a resistance at the standard temperature.

$$N_a = (\overline{EN})kT_0 \text{ watts/cycle} \qquad (3.47)$$

where

$\overline{EN}$ = external noise factor.

Some works refer only to the equivalent temperature of the antenna resistance, $T_A$. In that case,

$$(\overline{EN}) = \frac{T_A}{T_0} \qquad (3.48)$$

where $T_A$ = equivalent noise temperature of the antenna.

The value of $(\overline{EN})$ is frequency dependent and some equations giving values for it are presented by Norton and Omberg.[48] For more up-to-date information on the temperature seen by an antenna pointed at the sky the reader is referred to the literature on radio astronomy, which contains extensive studies of this factor.

Referring to the section on noise source temperatures, it can be seen that the external noise factor could also be called the "relative noise temperature of the source".

The most complicated situation that might exist is to calculate the external noise factor of an antenna for which the ohmic resistance is not negligible, and the antenna is at some ambient temperature other than the standard or the equivalent temperature of the radiation resistance. Assume that the antenna has a radiation efficiency of $\gamma$; for every unit of power supplied to the terminals, $\gamma$ is radiated and $(1-\gamma)$ is dissipated in the ohmic resistance as losses. Then

$$(\overline{EN}) = \frac{\gamma T_{amb} + (1-\gamma)T_{rad}}{T_0} \qquad (3.49)$$

where $T_{amb}$ = temperature of the ohmic resistance.

$T_{rad}$ = temperature "seen" by radiation resistance

$\gamma$ = antanna radiation efficiency.

Similarly,

$$T_A = \gamma T_{rad} + (1 - \gamma)T_{amb} \qquad (3.50)$$

## IV. NOISE IN PASSIVE NETWORKS

Thus far, only the problems of noise in active linear networks and noise in antenna systems have been considered. Attention will now be turned to passive linear networks, for example, an r-f tuned circuit, an attenuator pad, or a transmission system of waveguide or some other material. Networks of this type are characterized by a gain (always less than one) and a bandwidth. See Fig. 4.1.

In a manner analogous to the case of an antenna with a radiation resistance and an ohmic resistance, each at a different "temperature", the situation often occurs in which a passive network is at one temperature and its source at another. In both cases the quantity of interest is the apparent or equivalent temperature at the output terminals, and it is found that very similar results apply, although the physical causes are quite different. Consider the situation shown in Fig. 4.2(a), with both the source and the network at some temperature $T_1$. With the entire system at the same temperature, the noise power output of the network must be given by

$$N_0 = kT_1B. \qquad (4.1)$$

If it is next assumed that the temperature of the network is $0^oK$, there will be no contribution to the noise power output by any of the resistive elements in the network. See Fig. 4.2(b). The noise power output will then be

$$N_0' \text{ (due to source only)} = kT_1BG_0 \qquad (4.2)$$

The quantity of primary interest is the noise added by the network, and its value can be found by now assuming the source to be at $0^oK$ [Fig. 4.2(c)]. Then the network noise is the difference between the total noise and the noise due to the source, or

$$N_0'' \text{ (due to network)} = kT_1B(1-G_0) \qquad (4.3)$$

These expressions can then be generalized to obtain the one given below. Note that the source temperature in this equation may be the equivalent temperature at the output of a preceding network.

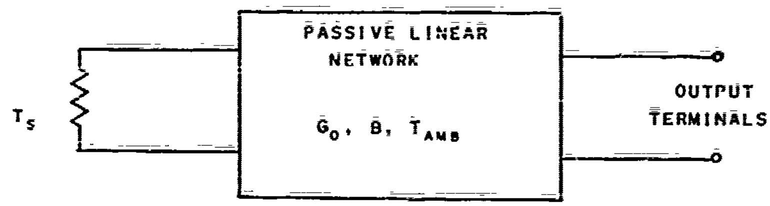



FIG. 4.1. Passive linear network.

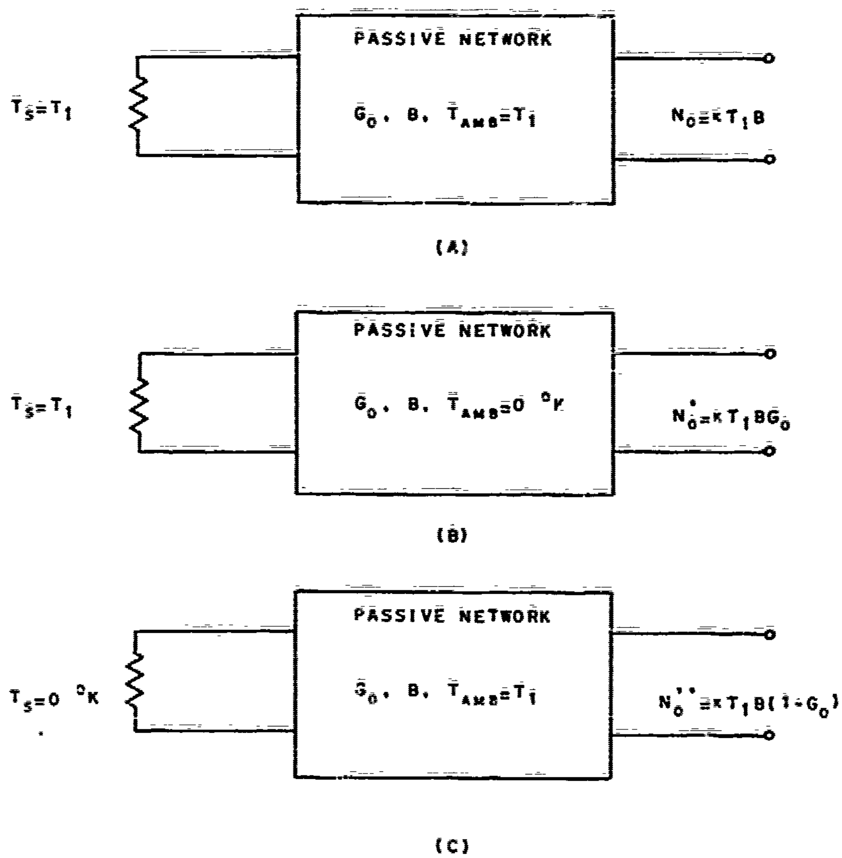



FIG. 4.2. Derivation of the noise factor of a linear passive network.

$$T_{eq} = G_0(T_s) + (1 - G_0)(T_{amb}) \qquad (4.4)$$

where $T_{eq}$ = equivalent output noise temperature of the source and the network combined

$T_s$ = equivalent temperature of the source

$T_{amb}$ = ambient temperature of the passive network.*

The closer the gain of the network is to unity the nearer the equivalent output noise temperature approaches the source temperature. For this reason the noise introduced by very-low-loss passive networks is often neglected completely.

Treating the noise in a passive network by temperatures, as above, is perfectly acceptable at all times. In fact, this method is perhaps the easiest way to handle the problem when an antenna transmission line is being considered. However, when the passive network is in the receiver proper, it is inconvenient to have to deal with both temperatures and noise factors. For that reason, the noise factor for the passive network will be derived.

From the expression above the equivalent output noise temperature of the network can be found.

$$T_{eq} = G_0 T_s + (1 - G_0)T_{amb} \qquad (4.4)$$

To convert any noise temperature into an equivalent noise power density, multiply the temperature by Boltzmann's constant, k:

$$kT_{eq} = kG_0 T_s + k(1 - G_0)T_{amb} \qquad (4.5)$$

*When the ambient temperature of the network is not the same for the entire network, special problems are encountered. A good example of this situation is a waveguide connecting a source at a reduced temperature (in liquid helium) to a network at room temperature. This problem was examined by Maxwell and Leon.[37]

Referring to Tables III-2(a) and (c) in the preceding section, it can be seen that this expression is now in the form of an equation for noise power densities.

$$\begin{bmatrix}\text{Total output noise} \\ \text{power density}\end{bmatrix} = \begin{bmatrix}\text{Amplified input} \\ \text{noise power} \\ \text{density}\end{bmatrix} + \begin{bmatrix}\text{Network excess noise} \\ \text{power density referred} \\ \text{to the output}\end{bmatrix} \quad (4.6)$$

Again referring to Table III-2(c), the last term can be converted to the form using the standard noise factor, and the following is obtained:

$$k\,(1 - G_0)T_{amb} = (\bar{F} - 1)kT_0G_0 \qquad (4.7)$$

$$(\bar{F} - 1) = \frac{(1 - G_0)}{G_0} \cdot \frac{T_{amb}}{T_C} \qquad (4.8)$$

$$\bar{F} = \left( \frac{(1 - G_0)}{G_0} \cdot \frac{T_{amb}}{T_0} \right) + 1 \qquad (4.9)$$

When the ambient temperature of the network is equal to the standard temperature, which is often an assumed condition, the above expression is greatly simplified:

$$\bar{F} = \frac{1}{G_0} \quad \text{for} \quad T_{amb} = T_0 \qquad (4.10)$$

or

$$\bar{F} = L \qquad (4.11)$$

Therefore, two conditions must combine to make it possible to neglect the noise added by a passive network in a system. The first of these is that the ambient temperature of the network must be equal to the standard temperature, and the second is that the maximum available power gain must be very close to unity. For lossy networks or unusual ambient temperatures it will be necessary to consider the excess noise added by the passive network. The very low values of the effective input noise temperature now possible with maser amplifiers require that noise in <u>all</u> lossy networks preceding the maser be considered if the correct value is to be obtained for the system noise factor.

## V. DESCRIBING NOISE IN CASCADED NETWORKS

### A. INTRODUCTION

In order to calculate the over-all system noise factor, it is essential to be able to derive the effective noise factor for several "noisy" linear networks that are connected in series as, for example, in a superheterodyne receiver. The technique for doing this will be developed for two networks, and then it will be shown how this same technique can be extended to any number of cascaded networks.

Perhaps the easiest way to visualize this problem is to use the equivalent block diagrams for the networks containing the excess-noise generators. See Fig. 5.1.

Using the basic definition of the noise factor, "ratio of actual output noise power to---amplified---thermal noise of the source", the development is easy to follow.

The calculations for the cascaded noise factor are made, assuming a source at the standard temperature, and then the over-all noise factor is modified if necessary.

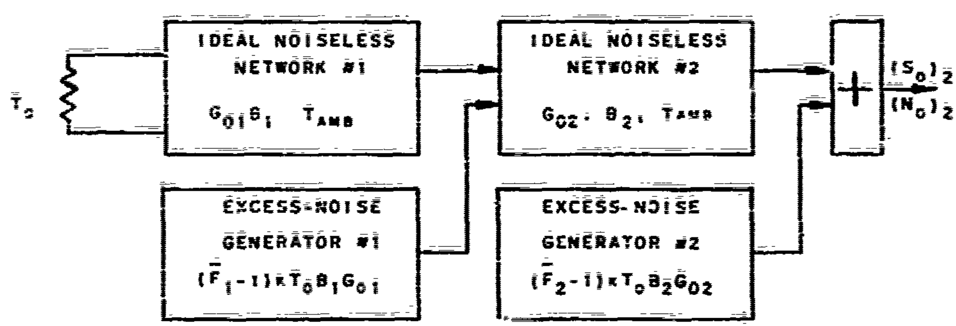



**FIG. 5.1. Equivalent block diagram of two noisy networks in cascade, both using the noise factor $\bar{F}$.**

## B. USING THE NOISE FACTOR

The input noise power, thermal noise of the source, is simply:

$$N_i = kT_0B_1 \tag{5.1}$$

The total noise output of the first network, which is also the noise power input to the second network, is

$$(N_0)_1 = kT_0B_1G_{0_1} + (\overline{F}_1 - 1)kT_0B_1G_{0_1} = \overline{F}_1kT_0B_1G_{0_1} \tag{5.2}$$

Then the total noise power output of the cascaded networks will be

$$(N_0)_2 = \overline{F}_1kT_0B_2G_{0_1}G_{0_2} + (\overline{F}_2 - 1)kT_0B_2G_{0_2} \tag{5.3}$$

The use of $B_2$ instead of $B_1$ in the term giving the value for the amplified noise power is justified as follows. At the output of the first network the total noise power was as given above (Eq. 5.2). Just as in the case of thermal noise in a resistive component, the noise power density here is assumed to be constant over the range of frequencies in the pass band of network No. 1. Therefore the noise power density at the input to the network No. 2 is

$$\overline{F}_1kT_0G_{0_1} \tag{5.4}$$

Since the bandwidth of network No. 2 is normally less than that of network No. 1 this value will extend over the entire band of network No. 2 and the input noise <u>power</u> to network No. 2 will be

$$\overline{F}_1kT_0B_2G_{0_1} \tag{5.5}$$

If the bandwidth of network No. 2 is greater than that of network No. 1 then the total noise power input to network No. 2 would be merely the output power of network No. 1; however, such a ratio of bandwidths would be unusual, so only the former case will be considered here.

The noise power in the output that can be attributed to amplified input noise from the source is

$$kT_0 B_{eff} G_{0_1} G_{0_2} \qquad (5.6)$$

For the same argument given above, this will represent frequency components only within the pass band of network No. 2 so that

$$(B_{eff})_{12} = B_2 \qquad (5.7)$$

The ratio giving the combined noise factor is then

$$\bar{F}_{1-2} = \frac{\bar{F}_1 kT_0 B_2 G_{0_1} G_{0_2} + (\bar{F}_2 - 1) kT_0 B_2 G_{0_2}}{kT_0 B_2 G_{0_1} G_{0_2}} \qquad (5.8)$$

$$\bar{F}_{1-2} = \bar{F}_1 + \frac{(\bar{F}_2 - 1)}{G_{0_1}} \qquad (5.9)$$

By a similar argument for three networks,

$$\bar{F}_{1-3} = \bar{F}_{1-2} + \frac{(\bar{F}_3 - 1)}{G_{0_1} G_{0_2}} \qquad (5.10)$$

$$\bar{F}_{1-3} = \bar{F}_1 + \frac{(\bar{F}_2 - 1)}{G_{0_1}} + \frac{(\bar{F}_3 - 1)}{G_{0_1} G_{0_2}} \qquad (5.11)$$

Extending the results yields

$$\bar{F}_{1-n} = \bar{F}_1 + \frac{(\bar{F}_2 - 1)}{G_{0_1}} + \frac{(\bar{F}_3 - 1)}{G_{0_1} G_{0_2}} + \dots + \frac{(\bar{F}_n - 1)}{G_{0_1} G_{0_2} G_{0(n-1)}} \qquad (5.12)$$

The expression for the system noise factor given in Eq. (5.12) is not exact; however, it is a close enough approximation for most purposes, including those of careful systems analysis. F man[11] gives the following exact equation for $\bar{F}_{1-2}$:

$$\bar{F}_{1-2} = \frac{\int F_1 G_{op2} G_{O1} df + \int (F_2 - 1) G_{op2} df}{\int G_{op2} G_{O_1} df} \tag{5.13}$$

where

$G_{op2}$ = operating gain of network No. 2

$G_{O_1}$ = available gain of network No. 1

Freeman further states that if the center frequencies of the two networks are the same, and $B_2 < B_1$, then:

$$\bar{F}_{1-2} = F_1 + \frac{\bar{F}_2 - 1}{G_{O_1}} \tag{5.14}$$

where $F_1$ = spot noise factor of network No. 1, evaluated at the center frequency.

If both networks have constant gain over their bandwidths and $B_1 = B_2$, then:

$$\bar{\bar{F}}_{1-2} = \bar{F}_1 + \frac{\bar{\bar{F}}_2 - 1}{G_{O_1}} \tag{5.15}$$

The differences between results obtained using Eqs. (5.13) and (5.15) are normally not significant.

If the noise factor for a cascade of networks is given,

$$\bar{F}_{1-n}$$

and the effective bandwidth of the system is known,

$$(B_{eff})_{1-n}$$

the total noise power in the output will be given by the following expression:

$$(N_O)_n = kT_0 (B_{eff})_{1-n} \bar{F}_{1-n} \tag{5.16}$$

## C. USING THE NOISE TEMPERATURE RATIO

As was shown in a preceding section, there are four common methods for describing the noise power output of the excess-noise generator. Then, considering only two networks in cascade, there are 16 possible ways to combine these various methods. In practice, few of these combinations are ever encountered; however, a combination that is of interest, since it represents a common situation, is a network using the noise temperature ratio followed by one using the standard noise factor. See Fig. 5.2.

In this case, the noise power output of network No. 1 is given by

$$N_{0_1} = kt_{r_1}T_0B_1 \tag{5.17}$$

and that of network No. 2 is

$$N_{0_2} = kt_{r_1}T_0B_2G_{0_2} + (\bar{F}_2 - 1)kT_0B_2G_{0_2} \tag{5.18}$$

With the same comments relative to $B_1$, $B_2$, and $B_{eff}$, here as given above, the combined noise factor is

$$\bar{F}_{1-2} = \frac{t_{r_1} + \bar{F}_2 - 1}{G_{0_1}} \tag{5.19}$$

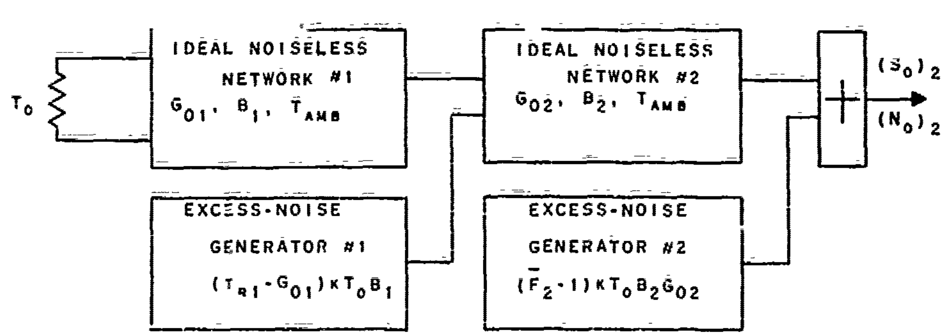



FIG. 5.2. Equivalent block diagram of two noisy networks in cascade, one using $t_r$ and one using $\bar{F}$.

## D. USING THE EFFECTIVE INPUT NOISE TEMPERATURE

A quantity that is extremely useful and convenient to work with is the effective input noise temperature of the over-all system. Knowing $T_{eff}$ for each network permits a direct computation of the over-all effective input noise temperature by a very simple formula.

Although there are several equally acceptable methods that might be used to derive an expression for $T_{eff_{1-n}}$, the easiest one to use here starts with the equations already given for the standard noise factor of a cascaded network.

From Eq. (     ) above

$$\bar{F}_{1-2} = \bar{F}_1 + \frac{(\bar{F}_2 - 1)}{G_{0_1}} \tag{5.20}$$

Using the substitution given in Table III-1, the noise factors can be converted to effective input noise temperatures.

$$(\bar{F} - 1)T_0 = T_{eff} \tag{5.21}$$

Then the expression for the cascaded effective input noise temperature is simply

$$T_{eff_{1-2}} = T_{eff_1} + \frac{T_{eff_2}}{G_{0_1}} \tag{5.22}$$

Starting with the expression for the general system noise factor

$$\bar{F}_{1-n} = \bar{F}_1 + \frac{(\bar{F}_2-1)}{G_{0_1}} + \frac{(\bar{F}_3-1)}{G_{0_1}G_{0_2}} + \dots + \frac{(\bar{F}_n - 1)}{G_{0_1}G_{0_2}\dots G_{0_{(n-1)}}} \tag{5.23}$$

the expression for the over-all system effective input noise temperature can be obtained.

$$T_{eff_{1-n}} = T_{eff_1} + \frac{T_{eff_2}}{G_{0_1}} + \frac{T_{eff_3}}{G_{0_1}G_{0_2}} + \dots + \frac{T_{eff_n}}{G_{0_1}G_{0_2}\dots G_{0_{(n-1)}}} \tag{5.24}$$

E. NOTE ON $B_1 < B_2$

The noise power output of network No. 1 is

$$N_{O_1} = \bar{F}_1 k T_0 B_1 G_{O_1} \quad (5.25)$$

The noise power output of network No. 2 is

$$N_{O_2} = \bar{F}_1 k T_0 B_1 G_{O_1} G_{O_2} + (\bar{F}_2 - 1) k T_0 B_2 G_{O_2} \quad (5.26)$$

Then,

$$\bar{F}_{1-2} = \frac{\bar{F}_1 k T_0 B_1 G_{O_1} G_{O_2} + (\bar{F}_2 - 1) k T_0 B_2 G_{O_2}}{k T_0 B_{eff} G_{O_1} G_{O_2}} \quad (5.27)$$

$$\bar{F}_{1-2} = \bar{F}_1 \left( \frac{B_1}{B_{eff}} \right) + \frac{(\bar{F}_2 - 1)}{G_{O_1}} \left( \frac{B_2}{B_{eff}} \right) \quad (5.28)$$

In cases such as these, where $B_1 < B_2$, there will usually be a third network with $B_3 < B_1$ so that the noise power output of network No. 3 is

$$N_{O_3} = \bar{F}_1 k T_0 B_3 G_{O_1} G_{O_2} G_{O_3} + (\bar{F}_2 - 1) k T_0 B_3 G_{O_2} G_{O_3} + (\bar{F}_3 - 1) k T_0 B_3 G_{O_3} \quad (5.29)$$

Then,

$$\bar{F}_{1-3} = \bar{F}_1 + \frac{(\bar{F}_2 - 1)}{G_{O_1}} + \frac{(\bar{F}_3 - 1)}{G_{O_1} G_{O_3}} \quad (5.30)$$

If such is not the case and all the networks following No. 1 have bandwidths greater than No. 1, the simplest approach to the problem is a solution similar to that used in Appendix C where the graphical representation of the bandwidths makes the calculations straight forward. Since the noise power density will not be constant, the output band must be divided into segments and then recombined after the noise power in each segment has been calculated.

PART THREE --- SYSTEM SENSITIVITY

## VI. GENERAL CLASSIFICATION OF RECEIVER AND DETECTION SYSTEMS

The procedure used to calculate the over-all sensitivity of a receiving system can be divided into two parts. The first of these is the determination of the magnitudes of the noise power associated with the pre-detection and post-detection portions of the system, considered separately. The second part of the calculation combines the pre-detection and post-detection noise at an appropriate point, the input to the detector, and determines the minimum detectable signal.

During the first phase of the calculations, all receiver systems separate into two natural groups:

1. The simple detector receivers (e.g., a simple crystal-video receiver).

2. Receiver with linear amplification of the signal preceding the detector (e.g., a crystal-video receiver with r-f preamplification, a superheterodyne receiver, or a trf receiver).

The only differences among the methods of calculation required for different types of receivers within each group are occasioned by the possible difficulty involved with "image channel" noise in the superheterodyne receiver.

For the second phase, the calculation of the minimum detectable signal, the previous classification of the system is ignored and it now falls into one of three categories:

1. Pre-detection and post-detection noise contributions are comparable, and both must be considered.

2. Pre-detection noise is much greater than post-detection noise, and post-detection noise may be ignored.

3. Post-detection noise is much greater than pre-detection noise, and pre-detection noise may be ignored.

Different techniques are required to determine the system sensitivity, depending upon which of the three above categories describe the system noise performance.

In Part Three of this report the nature of the calculations necessary to determine the system sensitivity will be explained by the use of general examples covering the crystal-video receiver with and without r-f preamplification, and the superheterodyne receiver. In the calculation to determine the minimum detectable signal it is assumed that the detector can be described by a square-law characteristic. This assumption is valid for nearly all detectors in their small-signal region.

## VII. THE SIMPLE DETECTOR - THE CRYSTAL-VIDEO RECEIVER

### A. INTRODUCTION

The simple detector receiver may take many forms from the iron-oxide rectifier or safety-pin and razor-blade detector to the highly complex traveling-wave-tube detector. Perhaps one of the most familiar forms of this type of receiver is the crystal-video microwave receiver using a specially designed detector crystal followed by a video amplifier with a bandwidth suitable for pulse reproduction.

The simple crystal-video receiver consists of a crystal detector followed by a suitable video amplifier. R-f selectivity can be provided if desired by means of tuned circuits ahead of the detector, and the system might be as shown in Fig. 7.1(a). This system would be satisfactory for receiving pulsed signals by detecting the video components of the spectrum of these signals in the crystal detector. The detector has been labeled a square-law device, since it follows a square-law characteristic at small-signal levels, and the small-signal region is of primary interest. If it is desired to use this system for the detection of c-w signals also, one method that can be used is to introduce a modulator preceding the detector so that video components will be present in the detector input signal when a c-w signal is received. See Fig. 7.1(b).

As will be seen later, the use of an r-f preselector will not normally improve the sensitivity of this type of receiver, since the noise level is set by the crystal detector. Although the presence of an r-f preselector narrows the r-f bandwidth and, hence, reduces the input noise power from the source, the excess noise of present crystal detectors is usually predominant.

### B. NOISE FIGURE AND EFFECTIVE BANDWIDTH

In referring to crystal detectors, the terms "noise figure" and "noise temperature" are not used, since these terms can be applied only to <u>linear</u> elements. Rather, the sensitivity of the detector with a given video amplifier having a specified bandwidth is used; this sensitivity

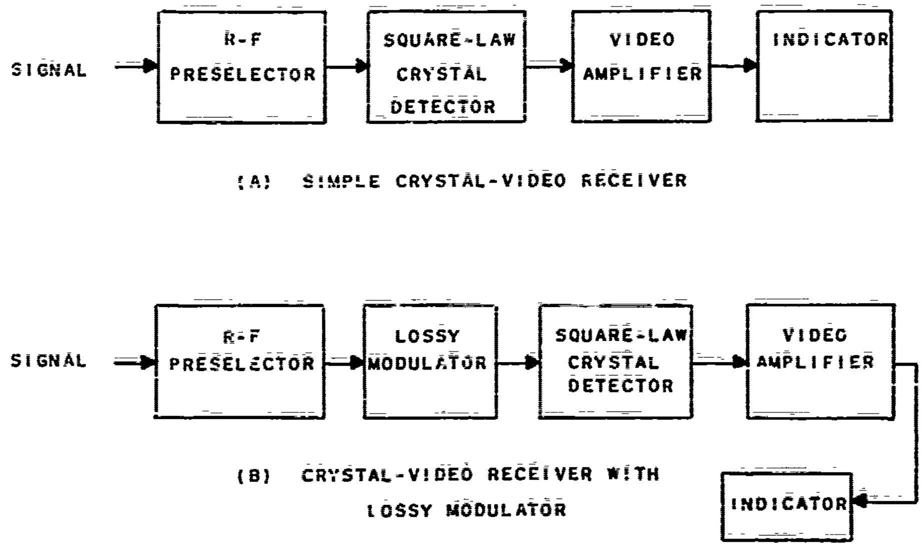



FIG. 7.1. **Block diagrams of crystal video receivers.**

is the amount of input signal power necessary to equal the detector-amplifier excess noise power, referred to the input of the detector. The equivalent input noise power of the detector-amplifier is specified as $S_x$. Therefore, if the input signal has a power equal to the value of $S_x$, the system output signal-to-noise ratio will be unity. Within certain limits it is possible to calculate the sensitivity of a particular detector-amplifier combination for some video bandwidth other than that used for the test measurements. (See Appendix A.)

Another term that does not have any significance for this particular network element is the "system effective bandwidth". In the simple crystal-video receiver the only "pre-detector noise" will be the small amount attributed to the source and to the r-f preselector. The post-detection noise generated in the crystal detector and the video-amplifier will be much greater than the pre-detection noise, and in this situation it is impossible to determine an effective bandwidth. It might be well to mention that for any type of system there is an "effective bandwidth" only if the post-detection noise contribution can be neglected completely.

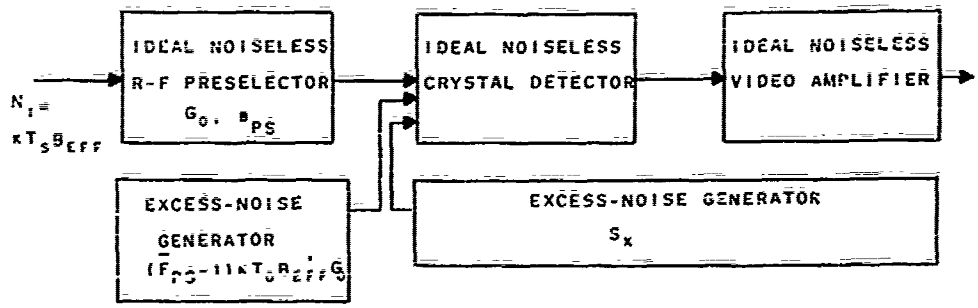



FIG. 7.2. Equivalent block diagram of crystal video receiver with r-f preselection.

## C. EQUIVALENT BLOCK DIAGRAM

To make the chosen approach as general as possible, and similar for both major classes of receivers, the simple crystal-video system may be represented as a combination of ideal devices and excess-noise generators. The antenna and transmission line are not shown as they have been treated separately. This method of portraying the system is somewhat unusual, but it will serve to bring out several important points and techniques.

From the measurements of the detector/video-amplifier sensitivity, $S_x$, it is possible to determine the total excess-noise power of this combination, referred to the detector input. This is shown as an excess-noise generator at the detector input. Also shown is an excess-noise generator for the preselector; and there would be one for the modulator also if one were used. See Fig. 7.2.

In the expression for the power output of the excess-noise generator for the preselector, as well as in the expression for the input noise power from the source, an effective bandwidth is used. It is necessary to use some bandwidth to determine the total noise power; however, this is not the effective bandwidth as defined in Section II-C.1, the bandwidth used with the system noise factor to obtain the system sensitivity, hence the prime on the symbol used here. Rather it is an effective bandwidth for the linear pre-detector portion of the system used only to specify the total noise power output of the linear system at the input terminals of the detector. The exact value of $B'_{eff}$ is not of interest, since it is never used in the calculation of the sensitivity of the simple crystal-video system.

## D. LIMITATIONS ON SENSITIVITY

As was mentioned earlier, it will be found that the sensitivity of this system will be set by the detector-amplifier noise for all present-day crystal detectors. Upon closer examination it is found that, in the present state of the art, the noise contributions of the crystal and that of the video amplifier are typically of the same order of magnitude. This means that an effort to improve the sensitivity by any great amount will require improvement of both components.

## VIII. RECEIVERS WITH LINEAR AMPLIFICATION PRECEDING THE DETECTOR

### A. INTRODUCTION

The second general class of receivers includes those that have active linear networks, preceding the detector, that amplify the incoming signal as well as amplify input noise from the source and introduce excess noise themselves. There are many examples of this type of system as well as numerous variations of each. In this section only two specific examples will be considered: the crystal-video system with r-f preamplification, and the superheterodyne system.

The techniques leading to the desired intermediate result, the noise power density of the linear system output, are almost identical for the two examples chosen, and for any system that falls into this broad class. There are several difficulties that may arise, such as the image response of the superheterodyne receiver, that are peculiar to a given configuration; however, it will be possible to mention only a few of these.

### B. CRYSTAL-VIDEO RECEIVER WITH R-F PREAMPLIFICATION

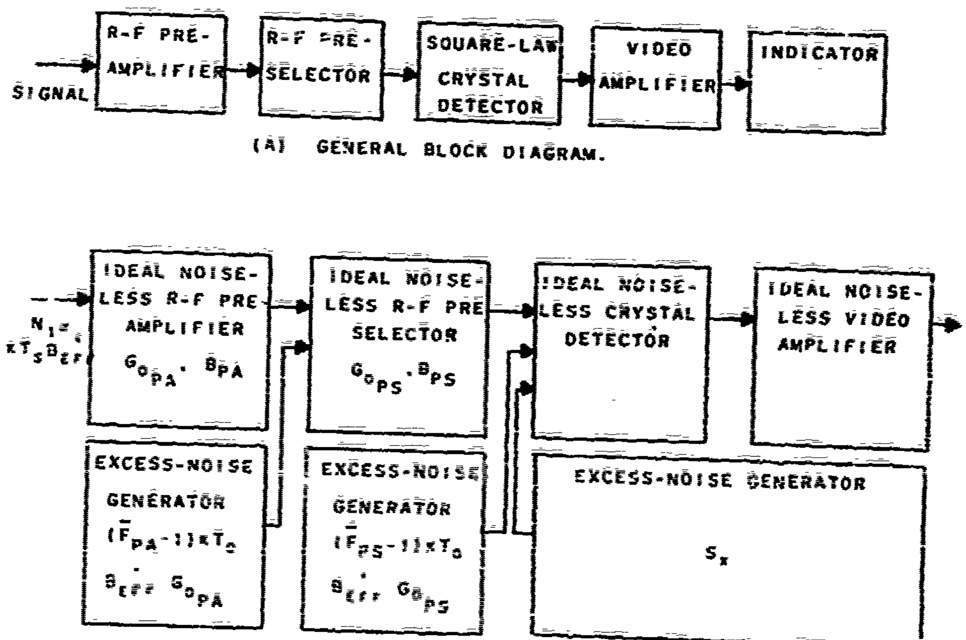
1. INTRODUCTION. It is possible to use an r-f preamplifier with the simple crystal-video receiver, to increase the system sensitivity by amplifying the incoming signal. Of course, the use of a preamplifier will also introduce excess noise which will set a limit on the ultimate sensitivity that can be obtained. There are two particular configurations of the crystal-video system with preamplification that are of great interest in this study. The first of these is merely a fixed-frequency r-f preamplifier that has a wide acceptance band, permitting the monitoring of a large r-f bandwidth with no frequency resolution within the band. The second configuration of interest is a receiver using a narrow-band preamplifier that is tuned across the total bandwidth to be observed. This is known as the "sweeping-filter receiver" and is a form of the common tuned-radio-frequency receiver.

2. EQUIVALENT BLOCK DIAGRAM. The crystal-video system with r-f preamplification may be represented by the block diagram shown in Fig. 8.1(a). Using the technique described in the preceding section, the noise power introduced by the detector-amplifier combination may be referred to the input terminals of the detector. Then, using standard techniques for linear networks, the excess noise for the preamplifier can be referred to the input terminals of the preselector when the preamplifier is described by a gain, bandwidth, and noise figure. See Fig. 8.1(b).

One quantity of interest is the noise factor of the linear portion of this receiver, which will be used to obtain the noise power density at the detector input. Using the earlier work on cascaded networks, this quantity can be derived directly.

$$\bar{F}_L = \bar{F}_{PA} + \frac{(\bar{F}_{PS} - 1)}{G_{O_{PA}}} \tag{8.1}$$

where $\bar{F}_L$ = noise factor of the linear portion of the system from the receiver input terminals to the detector input.




(B) EQUIVALENT BLOCK DIAGRAMS SHOWING NOISE SOURCES.

FIG. 8.1. Crystal video receiver with r-f preamplification.

3. MAXIMUM SENSITIVITY ATTAINABLE. There is a definite limit to the maximum sensitivity that can be attained, using an r-f preamplifier with a crystal-video system. As the gain of the preamplifier is increased, its excess noise power output referred to the detector input will increase until it exceeds the detector-amplifier excess noise power referred to the same point. After this point is reached there is little advantage, from the point of view of sensitivity alone, to further increases in preamplifier gain.[4]

C. SUPERHETERODYNE RECEIVERS

1. INTRODUCTION. The second example of a receiver employing predetector amplification is the superheterodyne system. The design of the superheterodyne receiver has become fairly well standardized. However, there are several special forms of it, such as double-conversion receivers, which will not be considered here, although their treatment is exactly analogous to that presented for the single-conversion receiver. The normal superheterodyne receiver consists of a radio-frequency preamplifier (which may be omitted), a radio-frequency preselector, a local oscillator and mixer combination which is often referred to as a converter, an intermediate-frequency amplifier, a second detector, and an audio- or video-frequency amplifier, (this study is primarily interested in video-frequency ranges), and an indicator. It is not the purpose of this study to examine the operation of the receiver. In this section the only item of interest is the noise characteristic of the receiver and the linear system noise factor, which will be used later to calculate the sensitivity of the entire system.

The two forms of the superheterodyne receiver to be considered are shown in Fig. 8.2. I-f filters may be included within the i-f amplifier, or separately.

2. PANORAMIC RECEIVERS. In this study, a configuration of particular interest is the class of superheterodyne receivers employing sweeping local oscillators---the "gliding-tone" receiver or, as it is more commonly known, the "panoramic receiver". With two exceptions,

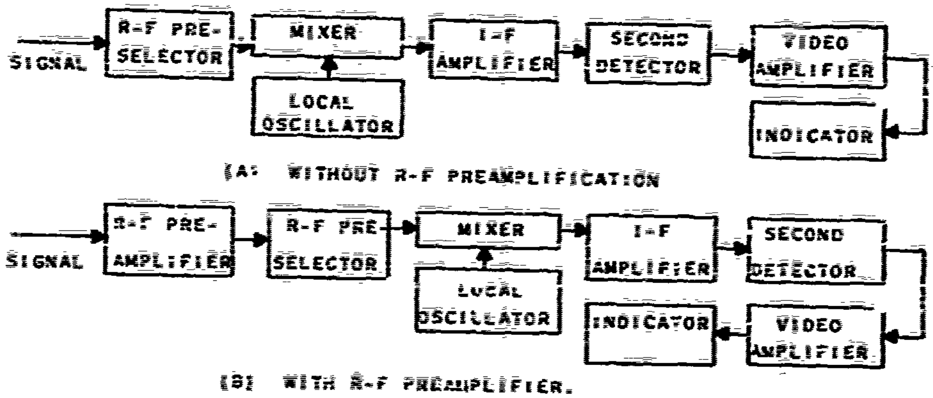



FIG. 8-2. Block diagrams of superheterodyne receivers.

the problems of image response and noise bandwidth,* the methods of examining both the repetitive sweeping and the manually tunable superheterodyne receivers are identical, so there will be no distinction made between the two in the work that follows.

3. EQUIVALENT BLOCK DIAGRAMS. All of the stages of the superheterodyne up to the second detector are linear networks, and the techniques developed earlier to represent these stages by ideal networks and excess noise generators can be applied.

a. The simple superheterodyne receiver. Considering only the linear stages of the receiver, the equivalent block diagrams using excess-noise generators will be as shown in Fig. 8.3. Note that the r-f preselector is a completely passive network merely acting as a bandpass limiting the noise power input to the mixer. The necessity for this bandpass limiting of the noise is discussed in Appendix C where the contribution of the image frequencies is discussed. When there is r-f preamplification it is assumed that both the preamplifier and the

*See Appendices C and D.

preselector have the same bandwidth or that the bandwidth of the preselector is less, and it is this smaller value that determines the r-f bandwidth. The latter situation is that encountered in wideband traveling-wave-tube preamplifiers.

The noise figure representation of the excess-noise generators is shown in Fig. 8.3(a), and in Fig. 8.3(b) the excess-noise generator associated with the mixer has its power output specified, using the noise temperature ratio of the mixer.

The over-all linear system noise figure is given by the expression

$$\overline{F}_L = \overline{F}_{PS} + \frac{(\overline{F}_M - 1)}{G_{ops}} + \frac{(\overline{F}_{IF} - 1)}{G_{ops} G_{OM}} \tag{8.2}$$

where $\overline{F}_L$ = effective over-all noise factor of the line · system.

Using the noise temperature ratio as illustrated in Fig. 8.2(b), the system noise factor is now

$$\overline{F}_L = \overline{F}_{PS} + \frac{t_{rM} + \overline{F}_{IF} - 1 - G_{OM}}{G_{ops} G_{OM}} \tag{8.3}$$

or, using the more common conversion loss of the mixer,

$$L_M = \frac{1}{G_{OM}} \tag{.4}$$

the system noise factor now becomes:

$$\overline{F}_L = \overline{F}_{PS} + \frac{L_M}{G_{ops}} \left( t_{rM} + \overline{F}_{IF} - 1 - \frac{1}{L_M} \right) \tag{8.5}$$

b. The superheterodyne receiver with r-f preamplification. The equivalent block diagrams, with noise figures, are shown in Fig. 8.4. Now the linear system noise factor is changed by adding the preamplifier noise factor:

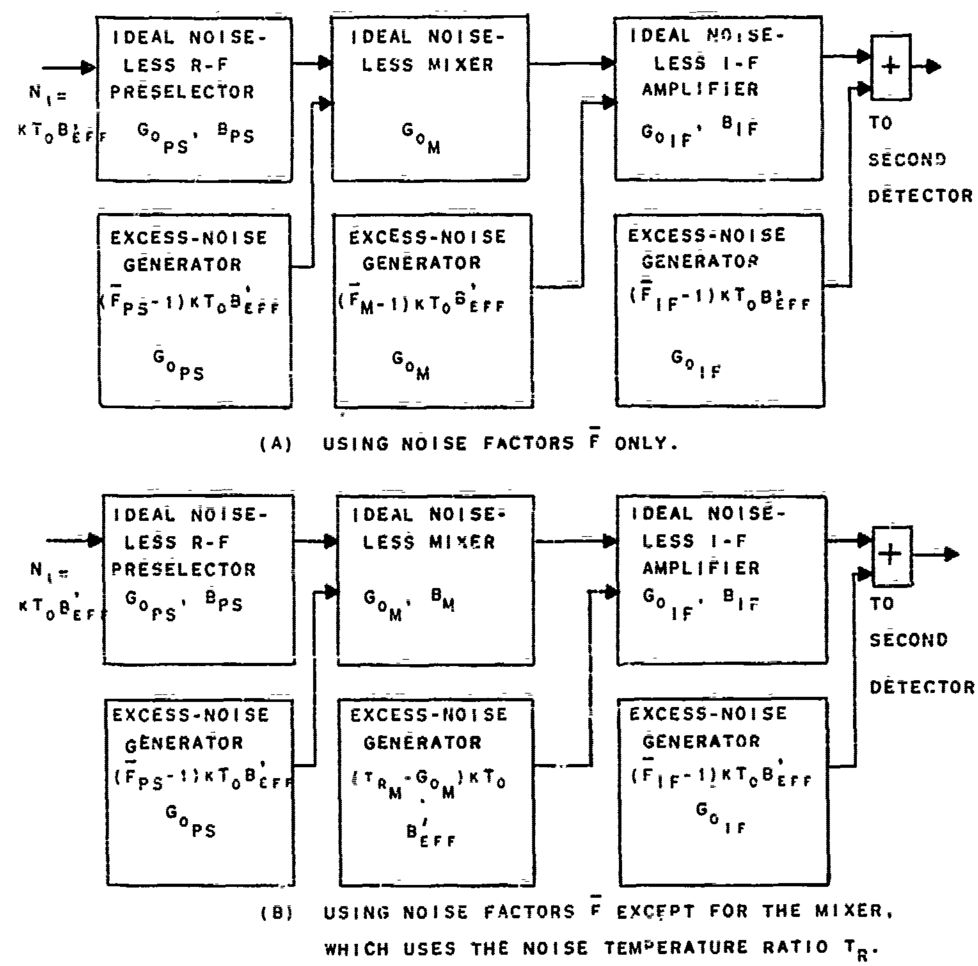



FIG. 8.3. Equivalent block diagrams of the linear predetection portion of a superheterodyne receiver without r-f preamplification.

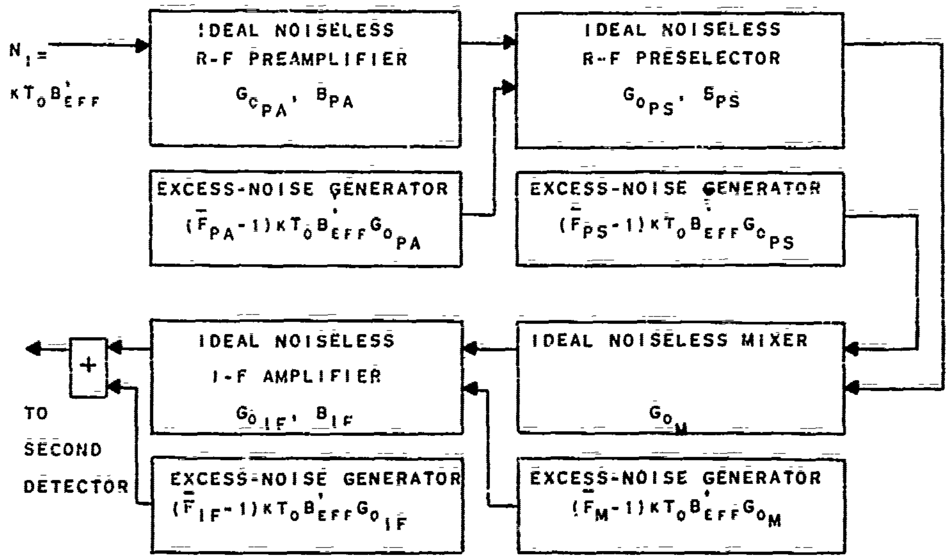



FIG. 8.4. Equivalent block diagram of the linear predetection portion of a superheterodyne receiver with r-f preamplification.

$$\overline{F}_L = \overline{F}_{PA} + \frac{(\overline{F}_{PS-IF} - 1)}{G_{opA}} \tag{8.6}$$

where $\overline{F}_{PS-IF}$ = the noise factor of the preselector/mixer i-f amplifier combination as calculated above when no preamplification was considered.

## D. IMPORTANT CHARACTERISTICS OF THE LINEAR SYSTEM

One of the two characteristics of the linear portion of the receiver system that will be essential to determining the system sensitivity, namely the linear system noise factor, has now been determined. The value of this parameter is obtained from the noise factors of the individual stages as well as their gains. It should be obvious that certain situations such as high gain and high noise factor in the preamplifier of the superheterodyne can make the noise factor of the linear system be approximately the same as that of the first active stage. The other important characteristic has been used in each block diagram, but only mentioned lightly. This is the effective bandwidth.

The effective bandwidth of the linear system, $B'_{eff}$, has been used in each excess-noise generator to specify the noise power output of that device. How to evaluate this bandwidth will be discussed later, as well as how to determine if the linear system effective bandwidth is the same as that of the entire receiver, $B_{eff}$.

# IX. CALCULATION OF SYSTEM SENSITIVITY

## A. INTRODUCTION

The key to calculation of the system sensitivity of the receiver is the examination of all noise and signal powers at the input to the detector. Here there is a logical dividing point in the receiver, with a linear system on one side and a nonlinear system on the other. In fact, it is impossible to find any other point in the system where the calculation can be made with any degree of facility. The linear-system noise cannot be referred to any point in the detector-video amplifier nor can the detector-amplifier noise be referred back into the linear system, for the over-all system effective bandwidth will not be known until after the sensitivity calculations have been completed.

## B. COMPARISON OF PRE-DETECTOR AND POST-DETECTOR NOISE POWER DENSITIES

1. INTRODUCTION. Before it is possible to determine the sensitivity of the system it must first be determined whether the detector/video-amplifier excess-noise power is significant when compared to the linear-system noise power at the detector input. This is a very simple statement to make; however, it cannot be executed quite so easily. The problem arises as to what the system effective bandwidth is so that the linear-system noise power may be calculated.

This problem can be circumvented by first calculating the noise power density, at the detector input, attributed to the linear system. Then an approximate noise power density will be determined for that part of the noise power attributed to detector-amplifier excess noise. These two densities can then be compared, and it will be possible to decide whether the detector noise should be considered.

2. LINEAR-SYSTEM OUTPUT-NOISE POWER DENSITY. In the descirption of the equivalent block diagram of each system it was shown how to obtain the noise factor for the linear portion of the system by very straight-forward methods.*

---

*If a superheterodyne system is being examined, be sure to check for image response. See Appendix C.

Referring to the tables appearing earlier in this report, it is seen that the output noise power density, with a source at some temperature other than the standard, is given by the following expression:

$$\overline{F}_s k T_s G_0 \tag{9.1}$$

where $k$ = Boltzmann's constant

$T_s$ = source temperature, $^{\circ}K$

$G_0$ = over-all gain

$\overline{F}_s$ = effective noise factor.

The noise factor calculated earlier for the linear system was the noise factor referred to the standard temperature, $290^{\circ}K$. Now, this must be converted to the source temperature reference:

$$\overline{F}_s = 1 + (\overline{F} - 1) \frac{T_0}{T_s} \tag{9.2}$$

where $\overline{F}$ = noise factor referred to the standard temperature

$T_0$ = standard temperature, $290^{\circ}K$.

However, the source temperature may not be known. Physically, it is the apparent temperature presented by the combination of the antenna and the transmission line system at the input terminals to the receiver.

The equivalent temperature of the antenna is discussed at length in Part Two of this report. All that is necessary is to transform this "temperature" through a lossy element, the transmission line system. There are a number of ways this could be done, but the simplest approach is the same technique as that used for the antenna with losses. There is a transmission line with a gain of $G_{TL}$, and it is at the ambient temperature. Then the source temperature seen by the receiver, $T_s$, is given by the following expression:

$$T_s = G_{TL} T_A + (1 - G_{TL}) T_{amb} \tag{9.3}$$

where $T_A$ = apparent antenna temperature.

Now, all the values necessary to calculate the desired noise power density by the formula given below are known.

$$D = \bar{F}_{SL} k T_s G_{OL} \quad \text{(watts/cycle)} \qquad (9.4)$$

where $D$ = noise power density at the detector input terminals attributed to the linear system output noise

$G_{OL}$ = gain of the linear system from the receiver input terminals to the detector input.

3. DETECTOR/VIDEO-AMPLIFIER NOISE-POWER DENSITY

a. Introduction. In the discussion of the simple crystal-video system in Section VII it was pointed out that the detector-amplifier excess noise referred to the detector input is obtained by measuring the minimum detectable signal power at the detector input. This is done for a particular crystal, crystal holder, crystal bias, video amplifier and video bandwidth; and the value obtained applies only with these particular components under the test conditions, except that the video bandwidth can be varied over a small range and a new value calculated. (See Appendix A.)

The value obtained for the excess noise of the detector-amplifier combination is a noise power. Before it is possible to calculate the equivalent detector noise-power density, $D_e$, to compare with the linear-system noise-power density, $D$, it is necessary to determine a value to use for the effective bandwidth.

b. Effective bandwidth. As was stated earlier, an effective bandwidth exists for a system only if the noise in the linear system is the governing factor in the over-all system sensitivity and if it is possible to completely neglect the detector/video-amplifier noise. Grigsby[19] has examined this problem at length and obtained values for the effective bandwidth for both c-w and pulse signals.

Since the detector is a square-law device, the output will contain terms resulting from three cross multiplications:

(1) (signal) x (signal)

(2) (noise) x (noise)

(3) (signal) x (noise).

Because of the "dual nature" of the third term it might be included as either noise or signal in the signal-to-noise ratio or it may be neglected completely, giving rise to three expressions for the output signal-to-noise ratio:

$$(1) \quad \frac{(s \times s)}{(n \times n)}$$

$$(2) \quad \frac{(s \times s) + (s \times n)}{(n \times n)}$$

$$(3) \quad \frac{(s \times s)}{(s \times n) + (n \times n)}$$

Before proceeding any further with the calculations, it is necessary to decide which one of these definitions for the signal-to-noise ratio will apply to the particular case under consideration. Once this decision is made, all remaining work must be consistant with it.

The effective bandwidths for pulse signals for each case, respectively, are:

$$(1) \quad \left[\frac{(s \times s)}{(n \times n)}\right] : \quad B_{eff} = (2b_L b_V - b_V^2)^{1/2} \tag{9.5}$$

$$(2) \quad \left[\frac{(s \times s) + (s \times n)}{(n \times n)}\right] : \quad B_{eff} = (2b_L b_V + 3b_V^2)^{1/2} - 2b_V \tag{9.6}$$

$$(3) \quad \left[\frac{(s \times s)}{(s \times n) + (n \times n)}\right] : \quad B_{eff} = (2b_L b_V + 3b_V^2)^{1/2} + 2b_V \tag{9.7}$$

where $\quad b_V^{2}$ = video bandwidth

$b_L$ = linear-system output bandwidth .

In the equations above, the following restrictions apply:

$$2b_V < b_L \tag{9.8}$$

and

$$b_V \approx 1/(\text{pulse length}) \tag{9.9}$$

If

$$2b_L \gg 3b_V \tag{9.10}$$

then all of the effective bandwidths for pulse signals reduce to

$$B_{eff} \approx (2b_L b_V)^{1/2} \tag{9.11}$$

The c-w case is not of as much interest; however, it is possible to obtain an effective bandwidth here also.

$$\left[\frac{(s \times s) + (s \times n)}{(n \times n)}\right]: \quad B_{eff} = 2b_L b_V - b_V^2 \tag{9.12}$$

Note that there is no square root here.

c. Detector noise-power density. Having chosen the desired definition for the signal-to-noise ratio, and calculated the effective bandwidth applicable, it is possible to determine an approximate value for the effective noise-power density attributed to detector-amplifier noise.

$$D_e = \frac{S_x}{B_{eff}} \tag{9.13}$$

Now compare the two noise power densities and determine which of three procedures to follow.

(1) $D_e \approx D$: Consider both linear system and detector noise

(2) $D_e \ll D$: Consider only linear system noise

(3) $D_e \gg D$: Consider only detector noise.

Up to this point, the calculations have involved many additions and subtractions, and the use of logarithms and decibels would have only complicated the problem rather than simplified it. From here on, most of the operations entail multiplication or division and the application of logarithms will be very useful.

The detector sensitivity, $S_x$, is normally given in dbm so the following expression can be used to obtain $D_e$ in dbm.

$$D_e = [S_x(\text{dbm}) - 10 \log_{10} B_{eff}] \text{ (dbm)} \tag{9.14}$$

And to obtain D in dbm, use the following:

$$D = 10 \log_{10} \bar{F}_s + 10 \log_{10} k + 10 \log_{10} T_s + 10 \log_{10} G_{O_L} \tag{9.15}$$

If the $B_{eff}$ used above in Eq. (9.14) was in cps,

$$D = (10 \log_{10}\bar{F}_s - 193.6 + 10 \log_{10}T_s + 10 \log_{10}G_{O_L}) \text{ (dbm/cycle)} \qquad (9.16)$$

or, if $B_{eff}$ was in Mc

$$D = (10 \log_{10}\bar{F}_s - 138.6 + 10 \log_{10}T_s + 10 \log_{10}G_{O_L}) \text{ (dbm/Mc)} \qquad (9.17)$$

C. CALCULATION OF MINIMUM DETECTABLE SIGNAL

1. REFERRED TO DETECTOR INPUT. Following the steps outlined above, it has been determined whether or not to consider the detector noise. Knowing this, it is possible to accurately calculate the signal strength necessary at the input terminals of the detector so that the minimum-detectable-signal criterion will be met at the output (output signal-to-noise ratio equal to unity).

The formulas for the three cases are very easy to apply, since all the values needed have already been calculated. $P'_{s\,min}$ will define the minimum detectable signal referred to the detector input terminals. The procedures to follow in each case are as follows.

a. Consider both linear-system and detector noise. For this case, there is a choice of three formulas depending on which definition was used for the signal-to-noise ratio at the output of the detector. (See Appendix B.) The definition used here must be the same as that used to determine $D_e$. Unfortunately, logarithms and decibels cannot be used here.

(1) $\left[\frac{(s \times s)}{(n \times n)}\right]$ : $P'_{s\,min} = [D^2(2b_L b_V - b_V^2) + S_x^2]^{1/2}$ (watts)

(9.18)

(2) $\left[\frac{(s \times s) + (s \times n)}{(n \times n)}\right]$ : $P'_{s\,min} = [D^2(2b_L b_V + 3b_V^2) + S_x^2]^{1/2} - 2Db_V$

(watts) (9.19)

(3) $\left[\frac{(sxs)}{(sxn) + (nxn)}\right]$ : $P'_{s\ min} = [D^2(2b_L b_V + 3b_V^2) + S_x^2]^{1/2} + 2Db_V$ (watts) (9.20)

b. <u>Consider only linear system noise.</u>

$$P'_{s\ min} = DB_{eff} \text{ (watts)} \tag{9.21}$$

$$P'_{s\ min} = 10 \log_{10} D + 10 \log_{10} B_{eff} \text{ (dbm)} \tag{9.22}$$

Here there is no prime on the effective bandwidth, for it applies to the entire system.

c. <u>Consider only detector noise.</u>

$$P'_{s\ min} = S_x \text{ (dbm)} \tag{9.23}$$

The last two cases lend themselves to the use of logarithms and it will be assumed that $P'_{s\ min}$ is in dbm in the next step.

2. REFERRED TO RECEIVER INPUT. Although the minimum detectable signal at the detector input is known, the system sensitivity has still not been obtained. If the system refers only to the receiver itself, then

$$P_{s\ min} = P'_{s\ min} - 10 \log_{10} G_{OL} \text{ (dbm)} \tag{9.24}$$

The antenna may also be considered an integral part of the system and the resulting sensitivity desired is the "wave front" power required for a minimum detectable signal.

$$P_{WF\ min} = P_{s\ min} - G'_{OTL} - G'_{OA} - 10 \log_{10} A \tag{9.25}$$

where $P_{WF\ min}$ = power in wave front per unit area, for minimum detectable signal in dbm per unit area

$A$ = capture area of the antenna; same units of area as $P_{WF\ min}$

$G'_{OTL}$ = transmission line gain in db

$G'_{OA}$ = actual measured antenna gain in db

## D. SUMMARY OF PROCEDURE TO CALCULATE SYSTEM SENSITIVITY

1. Determine the noise factor of the linear system from the receiver input terminals to the detector input:

$$\overline{F}_L$$

2. Using the standard noise factor of the linear system and the apparent source temperature, calculate the effective noise factor of the linear system:

$$\overline{F}_{sL} = 1 + (\overline{F}_L - 1)\frac{T_0}{T_s} \tag{9.26}$$

3. Using the effective noise factor, determine the noise power density due to the linear system referred to the detector input:

$$D = \overline{F}_{sL}\, kT_s G_{OL} \tag{9.27}$$

4. The excess noise power of the detector/video-amplifier combination, referred to the detector input, is obtained from test data:

$$S_x$$

5. The definition for the signal-to-noise ratio is chosen, and an approximate value for the equivalent noise-power density due to the detector-amplifier combination is calculated:

a. $\left[\frac{sxs}{nxn}\right]$ $$D_e = \frac{S_x}{(2b_L b_V - b_V^2)^{1/2}} \tag{9.28}$$

b. $\left[\frac{(sxs)+(sxn)}{(nxn)}\right]$ $$D_e = \frac{S_x}{(2b_L b_V + 3b_V^2)^{1/2} - 2b_V} \tag{9.29}$$

c. $\left[\frac{(sxs)}{(sxn)+(nxn)}\right]$ $$D_e = \frac{S_x}{(2b_L b_V + 3b_V^2)^{1/2} + 2b_V} \tag{9.30}$$

6. Compare the linear system noise power density and the detector-amplifier noise-power density. Then calculate the minimum detectable signal at the detector input:

a. $D_e \approx D$

$$\left[\frac{sxs}{nxn}\right] : P'_{s\,min} = [D^2(2b_L b_V - b_V^2) + S_x^2]^{1/2} \quad \text{(watts)} \tag{9.31}$$

$$\left[\frac{(sxs)+(sxn)}{(nxn)}\right] : P'_{s\,min} = [D^2(2b_L b_V + 3b_V^2) + S_x^2]^{1/2} - 2Db_V \quad \text{(watts)} \tag{9.32}$$

$$\left[\frac{(sxs)}{(sxn)+(nxn)}\right] : P'_{s\,min} = [D^2(2b_L b_V + 3b_V^2) + S_x^2]^{1/2} + 2Db_V \quad \text{(watts)} \tag{9.33}$$

b. $D_e \ll D$

$$\left[\frac{(sxs)}{(nxn)}\right] : P'_{s\,min} = D(2b_L b_V - b_V^2)^{1/2} \quad \text{(watts)} \tag{9.34}$$

$$\left[\frac{(sxs)+(sxn)}{(nxn)}\right] : P'_{s\,min} = D[(2b_L b_V + 3b_V^2)^{1/2} - 2b_V] \quad \text{(watts)} \tag{9.35}$$

$$\left[\frac{(sxs)}{(sxn)+(nxn)}\right] : P'_{s\,min} = D[(2b_L b_V + 3b_V^2)^{1/2} + 2b_V] \quad \text{(watts)} \tag{9.36}$$

c. $D_e \gg D$

$$P'_{s\,min} = S_x \quad \text{(dbm)} \tag{9.37}$$

7. Converting $P'_{s\,min}$ to dbm, it is then possible to determine the system sensitivity referred to the receiver input terminals:

$$P_{s\,min} = P'_{s\,min} - 10 \log_{10} G_{0L} \quad (dbm) \tag{9.38}$$

8. For the case for which $D_e \ll D$, the system noise factor is the same as the one that describes the performance of the linear portion of the system alone:

$$\overline{F}_{sys} = \overline{F}_L \tag{9.39}$$

9. For the special case of $D_e \ll D$, the system has an effective bandwidth given by one of three equations again dependent on the definition of the output signal-to-noise ratio.

$$\left[\frac{(sxs)}{(sxn)}\right] : B_{eff} = (2b_V b_L - b_V^2)^{1/2} \tag{9.40}$$

$$\left[\frac{(sxs)+(sxn)}{(nxn)}\right] : B_{eff} = (2b_V b_L + 3b_V^2)^{1/2} - 2b_V \tag{9.41}$$

$$\left[\frac{(sxs)}{(nxn)+(sxn)}\right] : B_{eff} = (2b_V b_L + 3b_V^2)^{1/2} + 2b_V \tag{9.42}$$

for $2b_L \gg 3b_V$, all three equations reduce to

$$B_{eff} = (2b_V b_L)^{1/2} \tag{9.43}$$

## PART FOUR --- SUMMARY

### X. SUMMARY AND CONCLUSIONS

Two main topics have been covered in this report: a unified description of the various terms used to describe the "noiseness" of a network and a general technique for the calculation of system sensitivity. The coverage of the "noise temperatures" is believed to be unique in this field, and is an attempt to bring some semblance of order into an extremely confusing subject. The definition of each noise temperature giving its physical significance will enable the systems engineer to better understand the meaning of each, and the conversion chart and other tables presented here will greatly assist him in their use.

The calculation of the system sensitivity of receiver systems is presented in such a way that any configuration can be examined using the same general principles. It should be immediately obvious that this treatment is not confined solely to receiver systems but is equally applicable to many other signal detection systems. One of the purposes of this part of the study was to bring together into one reference much of the material presently available only in specialized sources. Whenever a project such as this is attempted the author is in great danger of omitting many important topics that should have been included. In this vastly complicated subject this is certainly true, and this author only hopes that the shortcomings of this study motivate others to complete more adequate treatments of the subject. Before it is possible to suggest simplifications to any procedure presently in use it is essential to understand fully all of the facets of the problem. A work such as this is only the first step in this direction.

Part Three of this report on systems sensitivity should certainly lead to further work on the subject. However, Part Two on noise terms is probably complete as it is; and it might well serve as a signal to halt further work on this topic since the introduction of more terms can do little more than further confuse this already chaotic phase of systems analysis.

## PART FIVE --- APPENDICES

### APPENDIX A. VARIATION OF DETECTOR/VIDEO-AMPLIFIER SENSITIVITY WITH VIDEO BANDWIDTH

The detector/video-amplifier sensitivity, $S_x$, is a characteristic that is obtained by direct measurement of the sensitivity of a given detector and video amplifier combination. It may be desirable to obtain an estimate of what $S_x$ will be for a video bandwidth other than that used for the original measurement. This can be done as follows, assuming that the same video amplifier is used and only the video bandwidth is changed (amplifier noise factor stays the same).

$S_x$ is the total excess-noise power of the detector and video amplifier referred to the detector input.

$KS_x^2$ is the total excess-noise power referred to the amplifier output where K is a constant describing the gain characteristic of the detector and video amplifier combined.

If it is assumed that this total output noise power is uniformly distributed over the video passband, the noise power density at the output is

$$KS_x^2 \frac{1}{b_{VM}} \qquad \text{(A.1)}$$

where $b_{VM}$ = video bandwidth used in measuring $S_x$

For a different video bandwidth, $b_V$, the total noise power at the output will be

$$KS_x^2 \frac{b_V}{b_{VM}} \qquad \text{(A.2)}$$

Or referred back to the input, the sensitivity, $S_x'$, with the new video bandwidth, $b_V$, is now

$$S_x' = S_x \sqrt{\frac{b_V}{b_{VM}}} \qquad \text{(A.3)}$$

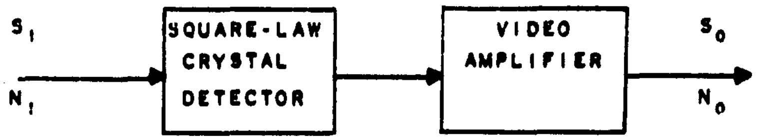
This relationship may be used for estimating the new sensitivity. It may become inaccurate if there is a very large change in the video bandwidth, for the assumption of uniformly distributed noise power in the output may not apply.

## APPENDIX B. MINIMUM DETECTABLE SIGNAL, CONSIDERING BOTH DETECTOR AND PREAMPLIFIER NOISE

Following the same technique as Grigsby and others, it is possible to determine the power requirement for the minimum detectable signal (output signal-to-noise ratio equal to one) for the case in which the detector-amplifier and the linear system noise powers, referred to the detector input, are of the same order of magnitude and both must be considered.

The form obtained for the answer indicates that there might be an "effective bandwidth" for the system, but this is not true, since $S_x$ also appears in the results, and this quantity cannot be expressed by the use of any bandwidth.

Consider only the system shown below where $S_1$ and $N_1$ represent the output of the linear portion of the system.




The detector/video-amplifier sensitivity, $S_x$, represents the signal power required at the input to the detector to obtain an output signal-to-noise ratio equal to unity when the linear system noise can be neglected completely. Therefore, $S_x$ represents the total excess-noise power of the detector/video-amplifier combination referred to the detector input.

Let K be a constant describing the action of the detector and video amplifier. (This result assumes that $b_V \approx \frac{1}{\text{pulse length}}$)

$$(s \times s \text{ term}): \quad S_0 = K (S_1)^2 \tag{B.1}$$

The total noise-power output is a combination of the input noise $N_1$ and the excess noise $S_x$. The part that can be attributed to the input noise is therefore given by the following expression:

$$K[D^2(2b_L b_V - b_V^2)] \qquad (B.2)$$

where D = noise-power density of $N_1$.

When the excess noise is added to this the total noise power at the output is then

$$(n \times n \text{ term}): \quad N_0 = K[D^2(2b_L b_V - b_V^2)+S_x^2] \qquad (B.3)$$

Considering only the (signal) x (signal) term and the (noise) x (noise) term, the output signal-to-noise ratio is given below:

$$\left[\frac{s x s}{n x n}\right] : \quad \frac{S_0}{N_0} = \frac{S_1^2}{D^2(2b_L b_V - b_V^2) + S_x^2} \qquad (B.4)$$

Setting this equal to one, the minimum detectable signal power referred to the detector input is given by the following expression:

$$\left[\frac{s x s}{n x n}\right] : \quad P'_{s\ min} = [D^2(2b_L b_V - b_V^2)+ S_x^2]^{1/2} \qquad (B.5)$$

Including the [(signal) x (noise)] term results are as below for pulse signals:

$$(s x n \text{ term}) : \quad K4S_1 D b_V \qquad (B.6)$$

$$\left[\frac{(s x s)+(s x n)}{(n x n)}\right]: \quad P'_{s\ min} = [D^2(2b_L b_V+3b_V^2)+S_x^2]^{1/2}-2Db_V \qquad (B.7)$$

$$\left[\frac{(s \times s)}{(n \times n)+(s \times n)}\right] : P'_{s\ min} = [D^2(2b_L b_V + 3b_V^2) + S_x^2]^{1/2} + 2Db_V \qquad (B.8)$$

The result, neglecting the [(signal) x (noise)] term, is the geometric mean of the other two.

## APPENDIX C. EFFECT OF INTERMEDIATE-FREQUENCY IMAGE BAND ON SYSTEM NOISE FACTOR

In the main body of the report the bandwidths of the stages of the system are not considered in detail as they have little actual bearing on the noise-power density at the output. The situation to be considered now is a case in which the bandwidths do affect the noise-power density through the contributions of the noise power in the image bands of the intermediate frequency.

In the frequency conversion action that takes place in the mixer a band of frequencies of the same bandwidth as the i-f amplifier is converted in frequency to the center frequency of the i-f stage. See Fig. C.1(a). This conversion is accomplished by having the local oscillator generate a frequency that differs from the value of the radio-frequency signal by an amount equal to the i-f center frequency.

Whether the local oscillator frequency is above or below that of the desired r-f band, there is another r-f band, the image band, that will also be converted to the center frequency of the i-f amplifier. The image band will be above or below the local oscillator frequency, opposite to the desired r-f band and at a distance in frequency equal to the i-f center frequency.

If the r-f pass band provided in the stage immediately preceding the mixer is similar to that shown in Fig. C.1(b), then there is no problem for there is no excess noise admitted at the image frequencies to be converted to the i-f frequency.

If, on the other hand, the r-f selector pass band is as shown in Fig. C.1(c), allowance must be made for the extra noise present in the image band. Since nearly all preamplifiers generate wideband excess noise, there will be noise power available at the image frequencies even if an earlier r-f selector has eliminated any signals in this band. The same comments apply in general even if there is no preamplifier.

An example that may point up some of the pitfalls in accurate noise calculations will be given below.

Assume that the system is as shown in Fig. C.2(a), with the respective bandwidths of the different stages being shown in Fig. C.2(b). The

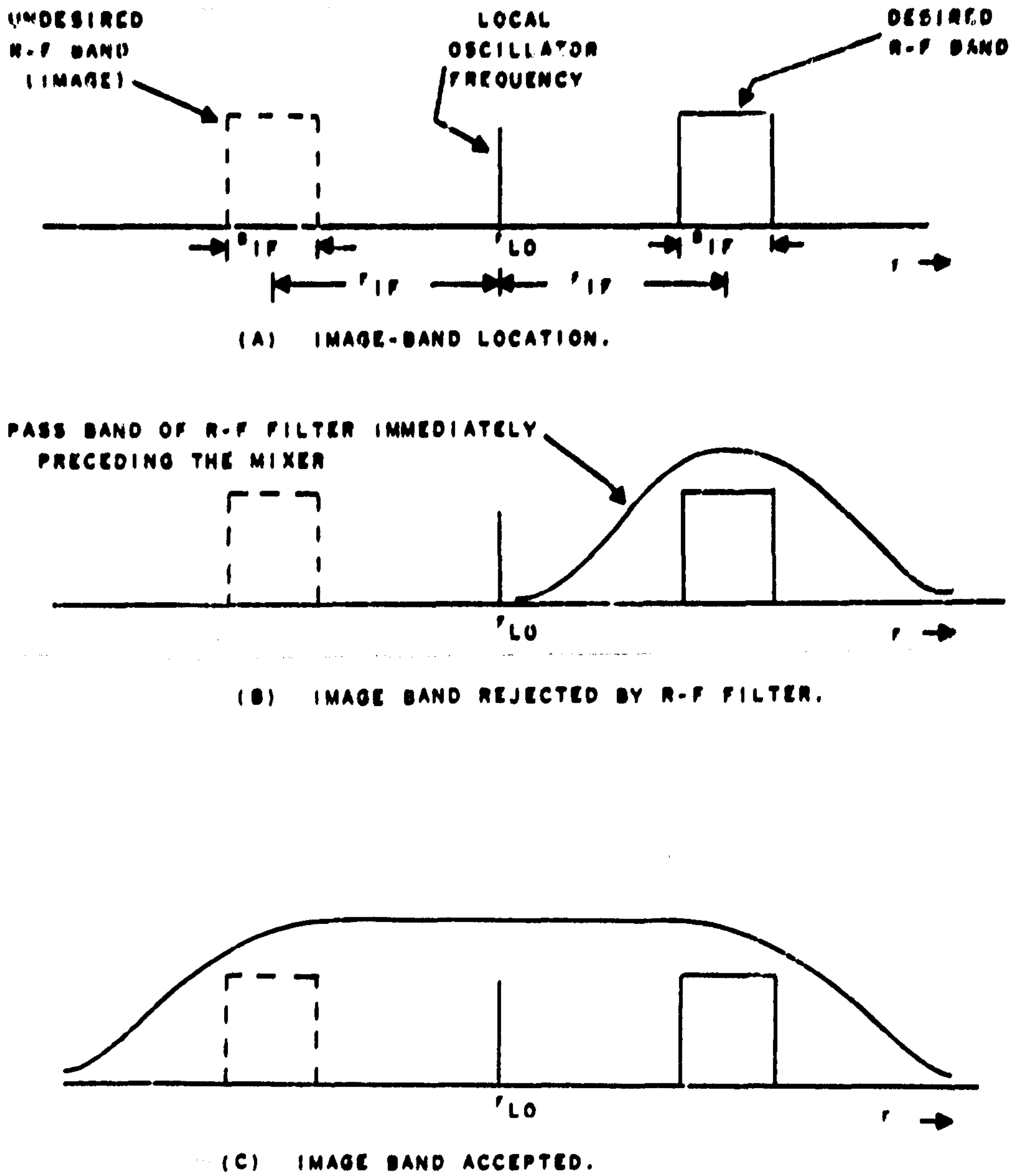



FIG. C.1. I-F image-frequency bands.

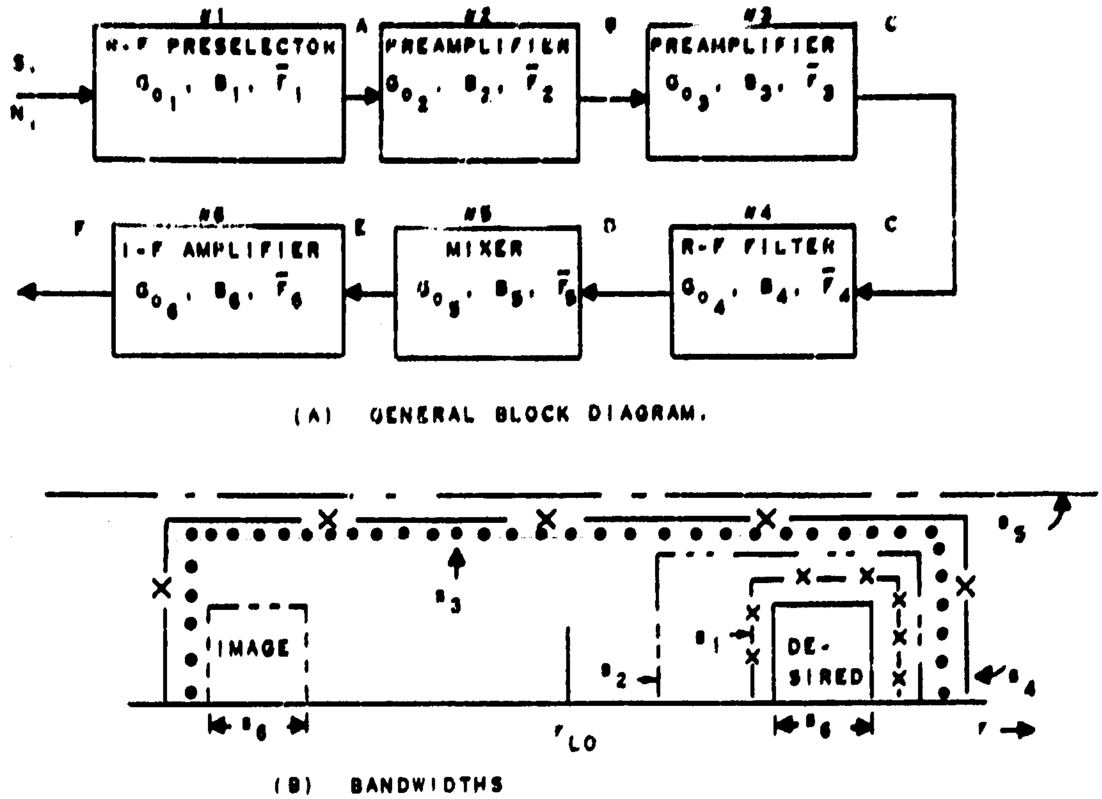



FIG. C.2. Superheterodyne with image-band acceptance.

entire system is at the standard temperature, to simplify calculations on the source and the passive elements, but this requirement is certainly not necessary. All bandwidths shown are the noise bandwidths. They refer to input signal pass bands and the frequency range of the ouput noise power due to excess network noise.*

---

*This may be considered to be a very arbitrary restriction, but it does apply in the majority of cases. It might well not be the case, however, for something such as a traveling-wave-tube amplifier that does not include a tuned circuit in the output as an integral part of the stage. As an example of the effect of having noise in the output at the image frequency, even though the image was not in the pass band, consider the first example given in this appendix. In this case the noise factor with image response would be given by the following expression. Compare with Eq. (C.13). (Note doubling of second term.)

$$\bar{F}_{1-6} = \bar{F}_1 + \frac{2(\bar{F}_2-1)}{G_{0_1}} + \frac{2(\bar{F}_3-1)}{G_{0_1}G_{0_2}} + \frac{2(\bar{F}_4-1)}{G_{0_1}G_{0_2}G_{0_3}} + \frac{(\bar{F}_5-2)}{G_{0_1}G_{0_2}G_{0_3}G_{0_4}} + \frac{(\bar{F}_6-1)}{G_{0_1}G_{0_2}G_{0_3}G_{0_4}G_{0_5}}$$

The first step is the calculation of the total output noise power due to the desired r-f band. The different points of interest will be referred to by letters shown in Fig. C.2(a).

For the desired r-f band (considering only that power that will eventually reach the output) the following values for the total noise power are obtained at the different points:

$$\text{"A"} = kT_0B_6G_{0_1}\bar{F}_1 \tag{C.1}$$

$$\text{"B"} = kT_0B_6[G_{0_1}G_{0_2}\bar{F}_1 + G_{0_2}(\bar{F}_2-1)] \tag{C.2}$$

$$\text{"C"} = kT_0B_6[G_{0_1}G_{0_2}G_{0_3}\bar{F}_1 + G_{0_2}G_{0_3}(\bar{F}_2-1)+G_{0_3}(\bar{F}_3-1)] \tag{C.3}$$

$$\text{"D"} = kT_0B_6[G_{0_1}G_{0_2}G_{0_3}G_{0_4}\bar{F}_1+G_{0_2}G_{0_3}G_{0_4}(\bar{F}_2-1)+G_{0_3}G_{0_4}(\bar{F}_3-1) + G_{0_4}(\bar{F}_4-1)] \tag{C.4}$$

$$\text{"E"}^{*} = kT_0B_6[G_{0_1}G_{0_2}G_{0_3}G_{0_4}G_{0_5}\bar{F}_1+G_{0_2}G_{0_3}G_{0_4}G_{0_5}(\bar{F}_2-1) + G_{0_3}G_{0_4}G_{0_5}(\bar{F}_3-1)+G_{0_4}G_{0_5}(\bar{F}_4-1)+G_{0_5}(\bar{F}_5-1)] \tag{C.5}$$

---

*Here the expression

$$kT_0B_6G_{0_5}(\bar{F}_5-1)$$

is used as the value for the excess noise added by the mixer. This means that it is assumed that the mixer image "termination" is at the standard temperature, i.e., "perfectly matched". If this cannot be assumed, it is necessary to treat the mixer noise by the following method:

$$\begin{bmatrix}\text{Total noise}\\ \text{power output}\\ \text{of the mixer}\end{bmatrix} = \begin{bmatrix}\text{Excess noise}\\ \text{added by the}\\ \text{mixer}\end{bmatrix} + \begin{bmatrix}\text{Amplified noise}\\ \text{signal}\\ \text{termination}\end{bmatrix} + \begin{bmatrix}\text{Amplified noise}\\ \text{image}\\ \text{termination}\end{bmatrix}$$

This is the reason for the quantity $(\bar{F}_M-2)$ that appears in some of the literature on mixers. Using the above equation, the following is obtained for the total noise-power output.

$$N_0 = kT_0B_MG_{OM}(\bar{F}_M-2) + G_{OM}N_{i\ sig} + G_{OM}N_{i\ image}$$

$$"F" = kT_0B_6[G_{O_1}G_{O_2}G_{O_3}G_{O_4}G_{O_5}G_{O_6}F_1+G_{O_2}G_{O_3}G_{O_4}G_{O_5}G_{O_6}(F_2-1)$$

$$+G_{O_3}G_{O_4}G_{O_5}G_{O_6}(F_3-1)+G_{O_4}G_{O_5}G_{O_6}(F_4-1)+G_{O_5}G_{O_6}(F_5-1)+G_{O_6}(F_6-1)] \qquad (C.6)$$

The value for the power of the amplified source noise at "F" is

$$kT_0B_6G_{O_1}G_{O_2}G_{O_3}G_{O_4}G_{O_5}G_{O_6} \qquad (C.7)$$

Using this, the over-all noise figure is then

$$\bar{F}_{1-6} = \bar{F}_1 + \frac{(\bar{F}_2-1)}{G_{O_1}} + \frac{(\bar{F}_3-1)}{G_{O_1}G_{O_2}} + \frac{(\bar{F}_4-1)}{G_{O_1}G_{O_2}G_{O_3}}$$

$$+ \frac{(\bar{F}_5-1)}{G_{O_1}G_{O_2}G_{O_3}G_{O_4}} + \frac{(\bar{F}_6-1)}{G_{O_1}G_{O_2}G_{O_3}G_{O_4}G_{O_5}} \qquad (C.8)$$

This result could have been obtained directly from an extension of the noise factor of cascaded networks as presented earlier, but the entire development was given here to point out the technique and lead up to the consideration of the image noise.

There will be a certain amount of noise in the output that can be attributed to the image band. It is not necessary to start considering the noise in the image band until point "C" since the second preamplifier stage was the first stage to have the image band in its pass band, and the image appears in the pass band of <u>all</u> stages from there to the mixer.

The noise power in the image band is then given by the following expressions, using the same notation as above.

Image band noise at "C" $= kT_0B_6[G_{O_3}(\bar{F}_3-1)]$ (C.9)

Image band noise at "D" $= kT_0B_6[G_{O_3}G_{O_4}(\bar{F}_3-1)+G_{O_4}(\bar{F}_4-1)]$ (C.10)

At the mixer this noise has now been translated to the i-f frequency along with the noise in the desired band, but it is important to include here only the noise that originated in the image band.

$$\text{Image band noise at "E"} = kT_0B_6[G_{0_3}G_{0_4}G_{0_5}(\bar{F}_3-1)+G_{0_4}G_{0_5}(\bar{F}_4-1)] \qquad (C.11)$$

There is no component of excess noise added here by the mixer since that is already included in the noise for the desired band. The same comment applies to the i-f amplifier output as given below.

$$\text{Image band noise at "F"} = kT_0B_6[G_{0_3}G_{0_4}G_{0_5}G_{0_6}(\bar{F}_3-1)+G_{0_4}G_{0_5}G_{0_6}(\bar{F}_5-1)] \qquad (C.12)$$

Now, to find the noise factor for the system, first add the noise in the image to that attributed to the desired band. After doing this it is found that the over-all noise factor has a larger value.

$$\bar{F}_{1-6} = \bar{F}_1 + \frac{(\bar{F}_2-1)}{G_{0_1}} + \frac{2(\bar{F}_3-1)}{G_{0_1}G_{0_2}} + \frac{2(\bar{F}_4-1)}{G_{0_1}G_{0_2}G_{0_3}}$$

$$+ \frac{(\bar{F}_5-2)}{G_{0_1}G_{0_2}G_{0_3}G_{0_4}} + \frac{(\bar{F}_6-1)}{G_{0_1}G_{0_2}G_{0_3}G_{0_4}G_{0_5}} \qquad (C.13)$$

Here, the noise in the signal band and that in the image band have been considered separately, so that the value $(\bar{F}_5-2)$ is used for the excess noise added by the mixer. See footnote page 87.

In effect, there has occurred an approximate doubling of the noise factor of stages 3 and 4. As explained above there is no effect on stages 5 and 6. If the pass band of the first preamplifier had included all the image, then the noise factor would have been, by inspection, the following value:

$$\bar{F}_{1\text{-}6} = \bar{F}_1 + \frac{2(\bar{F}_2-1)}{G_{O_1}} + \frac{2(\bar{F}_3-1)}{G_{O_1}G_{O_2}} + \frac{2(\bar{F}_4-1)}{G_{O_1}G_{O_2}G_{O_3}}$$

$$+ \frac{(\bar{F}_5-2)}{G_{O_1}G_{O_2}G_{O_3}G_{O_4}} + \frac{(\bar{F}_6-1)}{G_{O_1}G_{O_2}G_{O_3}G_{O_4}G_{O_5}} \qquad \text{(C.14)}$$

Continuing this one step further would show that unless the overall noise factor is effectively determined by the preamplifier alone it will never be quite doubled, even if there is no image rejection.

To complicate the situation somewhat, while illustrating that this problem can usually be solved by inspection, consider the situation wherein the pass bands are as in Fig. C.3(a). It would certainly be unusual to be faced with a problem such as this, but it will serve to illustrate the technique (this was solved by inspection).

$$\bar{F}_{1\text{-}6} = \bar{F}_1 + \frac{1.25(\bar{F}_2-1)}{G_{O_1}} + \frac{1.75(\bar{F}_3-1)}{G_{O_1}G_{O_2}} + \frac{2(\bar{F}_4-1)}{G_{O_1}G_{O_2}G_{O_3}}$$

$$+ \frac{(\bar{F}_5-2)}{G_{O_1}G_{O_2}G_{O_3}G_{O_4}} + \frac{(\bar{F}_6-1)}{G_{O_1}G_{O_2}G_{O_3}G_{O_4}G_{O_5}} \qquad \text{(C.15)}$$

Beware of the trap in a situation such as shown in Fig. C.3(b). Bandwidth No. 3 effectively limits noise caused by stage No. 2. Again, by inspection, the noise factor is as below.

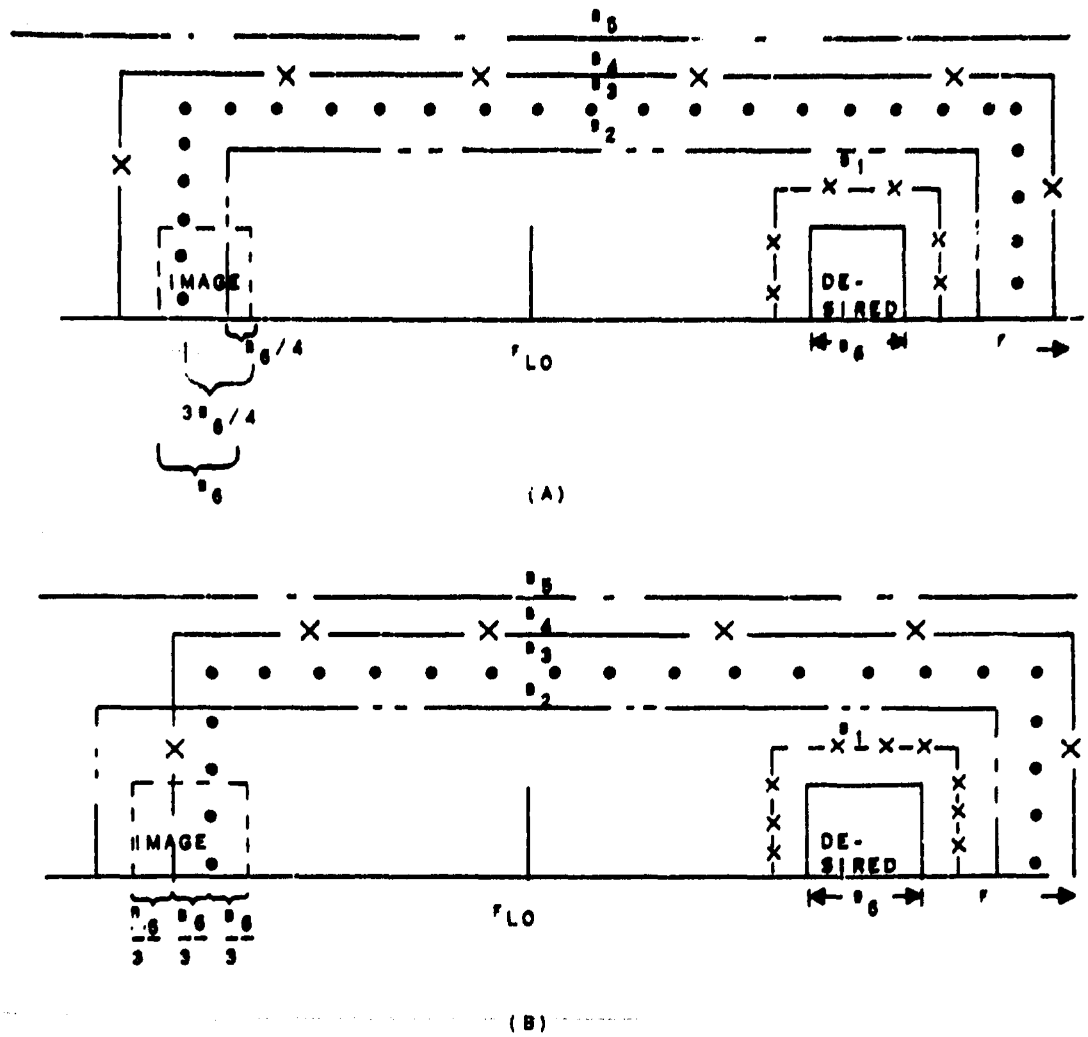



FIG. C.3. Superheterodyne with partial image-band acceptance.

$$\overline{F}_{1-6} = \overline{F}_1 + \frac{1.33(\overline{F}_2-1)}{G_{O_1}} + \frac{1.33(\overline{F}_3-1)}{G_{O_1}G_{O_2}} + \frac{1.67(\overline{F}_4-1)}{G_{O_1}G_{O_2}G_{O_3}}$$

$$+ \frac{(\overline{F}_5-2)}{G_{O_1}G_{O_2}G_{O_3}G_{O_4}} + \frac{(\overline{F}_6-1)}{G_{O_1}G_{O_2}G_{O_3}G_{O_4}G_{O_5}} \qquad (C.16)$$

## APPENDIX D. EFFECT OF SWEEPING LOCAL OSCILLATOR ON SUPERHETERODYNE RECEIVER NOISE BANDWIDTH AND IMAGE BAND NOISE

Consider now a situation similar to that just discussed in Appendix C, but in this receiver the local oscillator frequency will be swept through a range of frequencies in order to permit the narrow-band i-f to be tuned to a range of r-f frequencies. See Fig. D.1(a). The i-f bandwidth will be only a small fraction of the total bandwidth covered by the local oscillator, F. Of course, there must be an image band just as before, as shown in Fig. D.1(b). Of particular interest are the effects of noise added by this image; but first, the effects of noise in the desired band will be examined.

While in the sweeping mode, there is an apparent widening of the 3-db bandwidth of the i-f, accompanied by a decrease in gain in respect to the selectivity and amplification of signals. This effect has been examined elsewhere, but these results do not apply directly to the problem of noise so another approach must be used. J. L. Grigsby[19] made a thorough study of the repetitive sweeping local oscillator, the panoramic receiver, and obtained some results that will be very useful here. Specifically, he considered a sawtooth variation in frequency. Grigsby found that with a sawtooth-frequency-modulated local oscillator there was effectively a local oscillator frequency component every 1/T cycle throughout the range of frequency variation of the local oscillator where T is the period of one frequency sweep. Each of these components will translate the noise in narrow bands in both the desired and image bands down to the i-f frequency, but each one will do so with a much lower conversion gain than if the local oscillator had a fixed frequency. Putting his results into an equation, the following expression is obtained:

$$\begin{bmatrix}\text{Apparent}\\ \text{noise BW}\end{bmatrix} = \begin{bmatrix}\text{Number of}\\ \text{LO components}\\ \text{in the i-f band}\end{bmatrix} \begin{bmatrix}\text{Total BW}\\ \text{accepted}\end{bmatrix} \begin{bmatrix}\text{Effectiveness of}\\ \text{each LO component}\\ \text{as compared to a}\\ \text{fixed-frequency}\\ \text{LO}\end{bmatrix}.$$

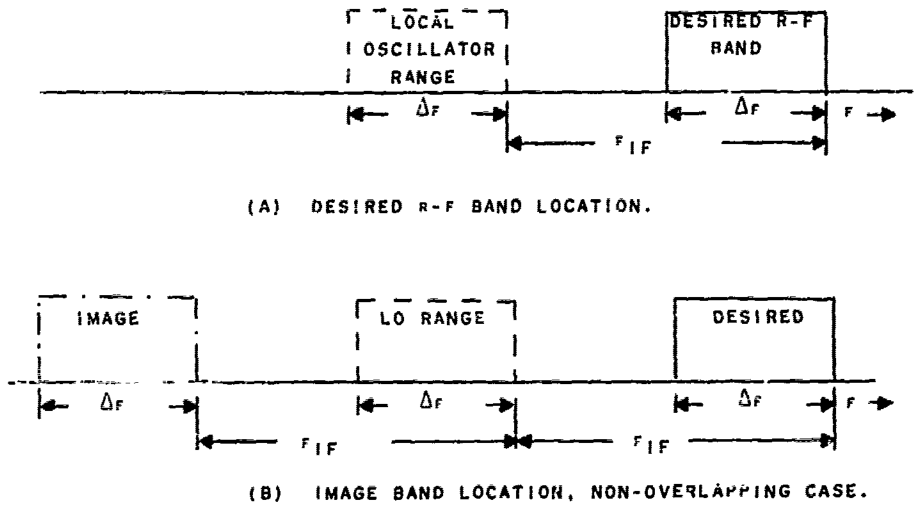



FIG. D.1. Frequency bands of sweeping-local-oscillator receiver.

$$B'_{IF} = \left( \frac{B_{IF}}{1/T} \right) \left( \Delta f' \right) \left( \frac{1/T}{\Delta f} \right)$$

Simplifying, it can be seen that for no image response, $\Delta f' = \Delta F$,*

$$B'_{IF} = B_{IF}$$

The complete theory behind this result is rather complicated, and the reader is referred to Grigsby's original work if he wishes more information.

The equation above will give the value of the apparent noise bandwidth. Now a step-by-step method to consider noise in the sweeping receiver will be presented. The same configuration as used before will

*It may appear that the total bandwidth accepted should be $\Delta f + B_{IF}$, since the local oscillator sweeps through a range $\Delta f$ and the i-f pass band will overlap the ends. This is true from the signal-acceptance point of view, but at each end there are only one-half as many local oscillator components in the i-f pass band, and these effects cancel each other so that the effective bandwidth accepted for noise purposes is $\Delta f$.

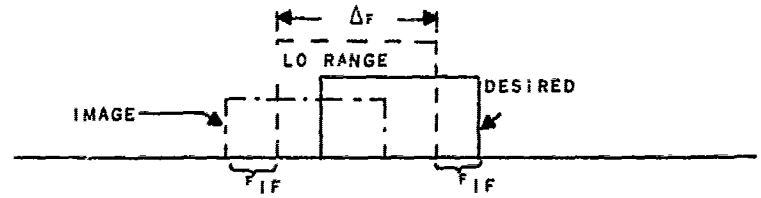



FIG. D.2. Location of image band, overlapping case.

be examined. See Fig. C.1(a). Note that now the local-oscillator frequency will be varying linearly with time.

A diagram of the pass bands will not be given, but the first case considered will be merely that one in which there is no image response. In this situation it should be easy to see that the noise factor will be unchanged.

$$\bar{F}_{1-6} = \bar{F}_1 + \frac{(\bar{F}_2-1)}{G_{0_1}} + \frac{(\bar{F}_3-1)}{G_{0_1}G_{0_2}} + \frac{(\bar{F}_4-1)}{G_{0_1}G_{0_2}G_{0_3}}$$

$$+ \frac{(\bar{F}_5-1)}{G_{0_1}G_{0_2}G_{0_3}G_{0_4}} + \frac{(\bar{F}_6-1)}{G_{0_1}G_{0_2}G_{0_3}G_{0_4}G_{0_5}}$$

There are two general situations as far as the image and desired bands are concerned. One of these is illustrated in Fig. D.1(b): the bands are completely separate. The other is shown in Fig. D.2: the bands overlap. It is also possible, in the first case, to have the bands overlap the range of frequencies of the local oscillator, as is always the case with overlaping image and desired bands. At first, it might be thought that there would be local-oscillator feed-through, since the i-f pass band will actually cover some of the local-oscillator components during the sweeping action. This does not occur because of the results of the vector addition of all of the components. What should be noticed is that, since part of the image is overlapped by the desired band in the second case, the noise in the overlapped portion is part of the "desired" noise and all that need be considered is the noise in that portion of the image band not overlapped, if it is not rejected by the pass bands of the stages preceding the mixer.

This would be an extremely long study if an attempt was made to cover every possible arrangement of pass bands with the two cases of overlap and non-overlap, but enough examples will be given to fully illustrate the technique. These results are all obtained merely by examining the pass band diagrams and using the technique developed in the section on non-sweeping local oscillators. The equation given above for the apparent noise bandwidth is the key to the entire solution.

First, examine the non-overlapping case. Pass bands are as in Fig. D.3(a).

$$\bar{F}_{1-6} = \bar{F}_1 + \frac{(\bar{F}_2-1)}{G_{0_1}} + \frac{2(\bar{F}_3-1)}{G_{0_1}G_{0_2}} + \frac{2(\bar{F}_4-1)}{G_{0_1}G_{0_2}G_{0_3}}$$

$$+ \frac{(\bar{F}_5-2)}{G_{0_1}G_{0_2}G_{0_3}G_{0_4}} + \frac{(\bar{F}_6-1)}{G_{0_1}G_{0_2}G_{0_3}G_{0_4}G_{0_5}}$$

This is the same result that was obtained for the non-sweeping case, but the reader should bear in mind that the phenomena causing it and the technique used to obtain the result are completely different. Examine the third term,

$$\frac{2(\bar{F}_3-1)}{G_{0_1}G_{0_2}} .$$

$$(\text{Multiplier}) = \frac{\begin{pmatrix}\text{Noise BW attributed}\\ \text{to desired band}\end{pmatrix} + \begin{pmatrix}\text{Noise BW attributed}\\ \text{to image band}\end{pmatrix}}{\begin{pmatrix}\text{Noise BW attributed}\\ \text{to desired band}\end{pmatrix}}$$

$$= \frac{B_{IF} + \left(\frac{B_{IF}}{1/T}\right)\begin{pmatrix}\text{Width of}\\ \text{image}\\ \text{overlapped}\end{pmatrix}\left(\frac{1/T}{\Delta f}\right)}{B_{IF}}$$

And in this particular example, with the width of the image overlapped equal to the total bandwidth $\Delta f$, the multiplier is equal to 2.

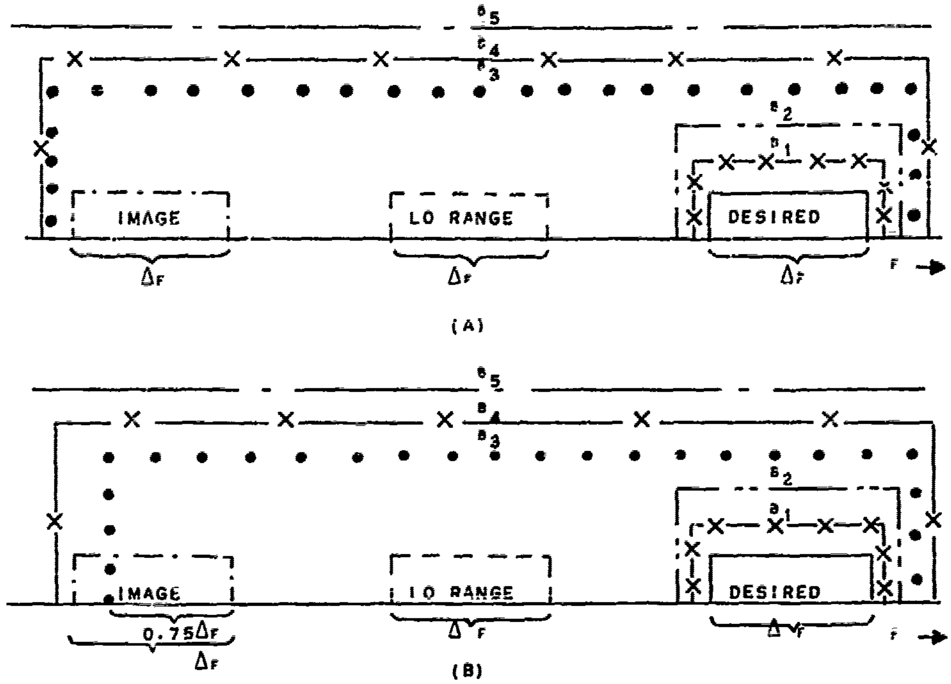



FIG. D.3. Image-band response, non-overlapping case.

Perhaps another example will clarify this point. Consider the pass bands as in Fig. D.3(b). For the fourth term there is no change, since its pass band completely overlaps the image; however, pass band No. 3 includes only 0.75 of the image. The noise factor is then changed so that

$$\overline{F}_{1\text{-}6} = \overline{F}_1 + \frac{(\overline{F}_2-1)}{G_{0_1}} + \frac{1.75(\overline{F}_3-1)}{G_{0_1}G_{0_2}} + \frac{2(\overline{F}_4-1)}{G_{0_1}G_{0_2}G_{0_3}}$$

$$+ \frac{(\overline{F}_5-2)}{G_{0_1}G_{0_2}G_{0_3}G_{0_4}} + \frac{(\overline{F}_6-1)}{G_{0_1}G_{0_2}G_{0_3}G_{0_4}G_{0_5}}$$

Not to pursue this point any longer, the overlapping case will now be considered. Remember that the "additional" noise added by the image is only that part that is in the portion of the image band not overlapped by the desired band.

Figure D.4(a) gives the pass bands for the first example. This is a trivial case:

$$\overline{F}_{1-6} = 1.5\,\overline{F}_1 + \frac{1.5(\overline{F}_2-1)}{G_{0_1}} + \frac{1.5(\overline{F}_3-1)}{G_{0_1}G_{0_2}} + \frac{1.5(\overline{F}_4-1)}{G_{0_1}G_{0_2}G_{0_3}}$$

$$+ \frac{(\overline{F}_5-2)}{G_{0_1}G_{0_2}G_{0_3}G_{0_4}} + \frac{(\overline{F}_6-1)}{G_{0_1}G_{0_2}G_{0_3}G_{0_4}G_{0_5}}$$

Now consider a more complex situation as in Fig. D.4(b):

$$\overline{F}_{1-6} = 1.2\overline{F}_1 + \frac{1.5(\overline{F}_2-1)}{G_{0_1}} + \frac{1.5(\overline{F}_3-1)}{G_{0_1}G_{0_2}} + \frac{1.5(\overline{F}_4-1)}{G_{0_1}G_{0_2}G_{0_3}}$$

$$+ \frac{(\overline{F}_5-2)}{G_{0_1}G_{0_2}G_{0_3}G_{0_4}} + \frac{(\overline{F}_6-1)}{G_{0_1}G_{0_2}G_{0_3}G_{0_4}G_{0_5}}$$

Note that pass band No. 4 effectively limits the second and third term multipliers by its width.

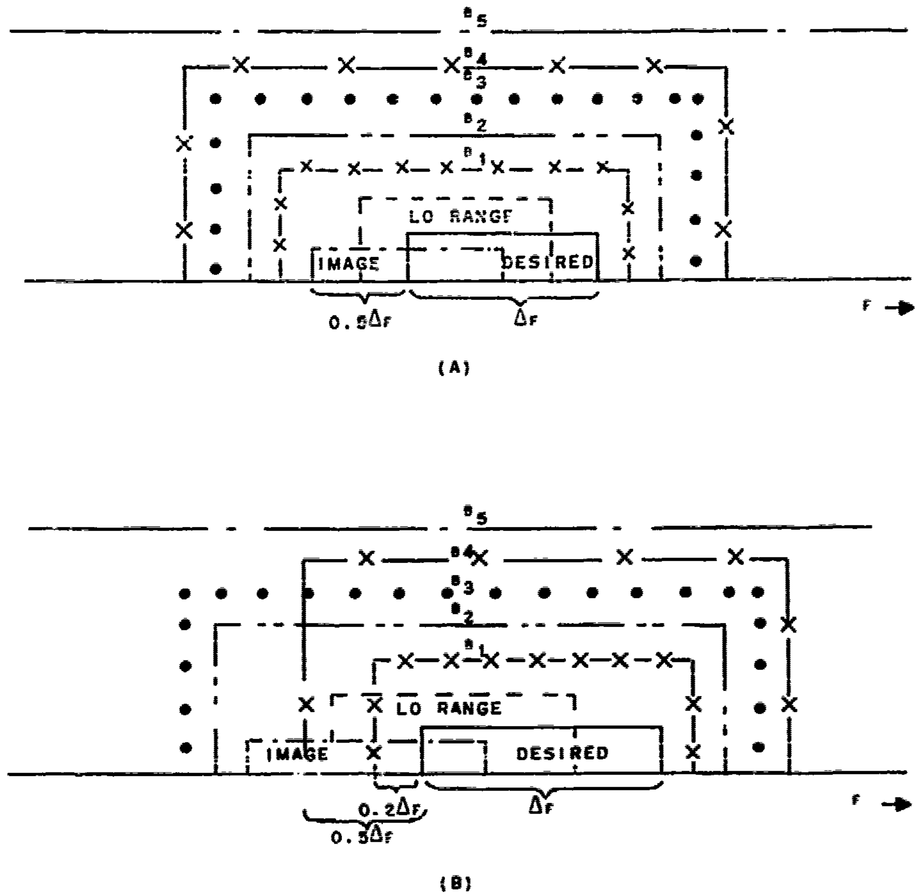



FIG. D.4. Image-band response, overlapping cases.

## BIBLIOGRAPHY

Arranged Alphabetically By Authors


1. R. B. Adler and H. A. Haus, "Network realization of optimum noise performance", IRE Trans. vol. CT-5, no. 3, September 1958, pp. 156-161.

(See also H. A. Haus)

2. Airborne Instruments Laboratory, Inc., (Advertisement), "Noise figure and measurements", The Pulse of Long Island---L. I. Section of the IRE, October 1956.
Describes some of the difficulties encountered in using temperature-limited diodes when measuring noise figures of extremely low-noise r-f amplifiers at 100-200 Mc.

3. _____, (Advertisement), "Noise figure measurements", The Pulse of Long Island---L. I. Section of the IRE, December 1956.
Problems encountered at higher frequencies indicate use of gas discharge tube for noise source.

(F. R. Arams: see A. L. McWhorter.)

4. W. E. Ayer, "Characteristics of crystal-video receivers employing r-f preamplification", Technical Report No. 150-3 [AF 33(600)-27784], Stanford Electronics Laboratories, Stanford University, Stanford, California, 20 September 1956.
"The operating characteristics of crystal-video receiving systems with r-f preamplification are discussed and equations given for the maximum sensitivity ($S_{max}$), and for the gain required in the preamplifier to realize $S_{max}$. Use of the equations is demonstrated by means of specific examples. An analysis of the behavior of this type of system is presented in the Appendix, the derivation of the $S_{max}$ equation being given there". The work presented here is not of a rigorous nature in the proofs, and the results require that the gain and noise figures be such that the detector/video-amplifier excess noise may be disregarded completely.

5. Bell Telephone Laboratories, Radar Systems and Components, D. Van Nostrand and Company, New York, 1949.
Little material other than basic definitions.

6. Julius S. Bendat, Principles and Applications of Random Noise Theory, John Wiley and Sons, Inc., New York, 1958.
Primarily concerned with random noise theory and associated mathematics, but this book does cover a little on thermal noise. Techniques for finding the output signal-to-noise ratios of various devices, such as detectors and correlators, are presented.

(R. N. Bracewell· see J. L. Pawsey.)

7. C. E. Chase, "Direct reading noise figure indicator", Electronics, November, 1955.
An instrument is described which makes possible direct reading of noise figure measurements with a minimum of adjustments required.

8. Seymour B. Cohn, "The noise figure muddle", The Microwave Journal, vol. 2, no. 3, March 1959, pp. 7-11.
Primarily interested in merely pointing out that certain problems do occur with image frequency channels. Cohn examines specifically the basic parametric amplifier with the added complications of pump and idle frequencies that contribute to the system noise. The article is an editorial, and the quantitative problem is not thoroughly covered.

9. Wilbur B. Davenport, Jr. and William L. Root, An Introduction to the Theory of Random Signals and Noise, McGraw-Hill Book Company, Inc., New York, 1958.
Contains a chapter on network noise figure, but most of the book is on the mathematics of random noise theory.

(John Ebert: see Arnold Newton.)

10. Harold J. Ewen, "A thermodynamic analysis of maser systems", The Microwave Journal, vol. 2, no. 3, March 1959, pp. 41-46.
An excellent discussion of the noise performance aspects of systems using maser amplifiers. Ewen points out that the rapid development of the maser "has stimulated a careful review of conventional methods of system noise analysis". The measure of noise performance that he advocates using is the effective input noise temperature. The analysis presented includes the effects of varying temperatures of the galactic background, ionosphere, atmospheric oxygen, atmospheric water vapor, and receiver noise. The paper derives the expression for the "system" temperature by including the effects of each component "temperature" weighted by the associated loss of each component.

(D. C. Forster: see Mr. R. Currie.)

11. J. J. Freeman, Principles of Noise, John Wiley and Sons, Inc., New York, 1958.
As well as dealing with the theory of random noise, this book also has a chapter on the noise factor and material on the accuracy of noise measurements.

12. H. T. Friis, "Noise figure of radio receivers", Proc. IRE, vol. 34, no. 7, July 1944, pp. 419-422.

"A rigorous definition of the noise figure of radio receivers is given in this paper. The definition is not limited to high-gain receivers, but can be applied to four-terminal networks in general. An analysis is made of the relationship between the noise figure of the receiver as a whole and the noise figure of its components. Mismatch relations between the components of the receiver and methods of measurement of noise figures are discussed briefly."

13. _____, and Dwight O. North, "Discussion on 'Noise Figures of Radio Receivers'", Proc. IRE, vol. 33, no. 2, February 1945, pp. 125-127.

Dr. North discusses several small points that vary between his work and that of Dr. Friis. This is mostly a problem of semantics, as is the entire field today. Dr. North does point out the problem of image band response and the fact that noise figures cannot be applied to non-linear parts of the receiver.

14. Edward L. Ginzton, Microwave Measurements, McGraw-Hill Book Company, Inc., New York, 1957.

Contains material on noise temperature of crystal and noise measurement techniques.

15. Harold Goldberg, "Some notes on noise figures", Proc. IRE, vol. 36, no. 10, October 1948, pp. 1205-1214.

"This paper takes up the basic ideas and definitions proposed by H. T. Friis and presents them in a form that is more easily understood. Naturally, complete generality is not achieved, and the conclusions are subject to restrictions. Nevertheless, useful results are obtained. Subjects treated include expositions of the meaning of 'available gain', and the derivation of simple noise-figure formulas for many types of circuits in common use." This paper is still confusing on the problem of source temperatures other than the standard.

16. Stanford Goldman, Frequency Analysis Modulation and Noise, McGraw-Hill Book Company, Inc., New York, 1948.

Of interest to this study are sections on receiver noise, noise measurement, noise figure, and thermal noise and radiation resistance.

17. Jack Greene, "Noise factor and noise temperature", Advertisement of the Airborne Instruments Laboratory, Inc., Proc. IRE, vol. 46, no. 1, January 1958.

Discussion of the effective noise temperature. This is direct measure of the noisiness of the network.

18. _____, B. Salzberg, and E. W. Sard, "Final engineering report on measurement of low noise figures---Assignment 12 J", Report No. 5208-1 [DA-49(170) SC-2555], Airborne Instruments Laboratory, Inc., Mineola, New York, January 1958.

Discusses method of measurement of low noise figure values using the Y-factor method. "In this method, two known amounts of available power (obtained from generators having the same impedance) are succesively applied to the input terminals of the network whose effective noise figure is to be measured. The resultant ratio of the output noise powers from the network is called the Y-factor and can be used to calculate the noise figure and effective input noise temperature of the network."

19. J. L. Grigsby, "An investigation of the sensitivity of some receivers having large r-f bandwidth", Technical Report No. 553-1 [DA 36(039)sc-73151], Systems Techniques Laboratory, Stanford Electronics Laboratories, Stanford University, Stanford, California, 4 November 1958.

Of primary interest to this study was the work on effective bandwidths of devices using square-law detectors.

20. Donald R. Hamilton, Julian K. Knipp, and J. B. Horner Kuper, Klystrons and Microwave Tubes, vol. 7, MIT Radiation Lab Series, McGraw-Hill Book Company, Inc., New York, 1948.

Primarily concerned with the noise produced by these particular devices. Many good definitions applicable to devices.

21. Robert C. Hansen, "Low noise antennas", The Microwave Journal, vol. 2, no. 6, June 1959, pp. 19-24.

This article begins by defining the three noise factors covered in the present report, using different terms ("the noise factor, $F_N$" for "the 'standard' noise factor, F"; "the degradation factor, $F_D$", for "the effective noise factor, $F_S$"; and "the sensitivity factor, $F_S$", for "the operating noise factor, $F_{op}$"). The technique of calculating the effective antenna temperature from the geometry of the antenna pattern is then described. The aspects of small-sidelobe antenna design are also covered.

(H. A. Haus: see also R. B. Adler.)

22. H. A. Haus and R. B. Adler, "Canonical form of linear noisy networks", IRE Trans., vol. CT-5, no. 3, September 1958, pp. 161-167.

23. _____ and _____, "Optimum noise performance of linear amplifiers", Proc. IRE, vol. 46, no. 8, August 1958, pp. 1517-1533.

24. _____ and _____, "Invariants of linear noisy networks", 1956 National Convention, IRE Convention Record, Part 2---Circuit Theory, March 1956, pp. 53-67.

25. _____ and _____, "An extension of the noise figure definition", Proc. IRE, vol. 45, no. 5, May 1957.
Presents new definitions to use in noise figure calculations when there is a negative output resistance in the network. New terms used are "exchangeable power" and "exchangeable power gain".

26. H. Heffner and G. Wade, "Gain, bandwidth and noise characteristics of the variable-parameter amplifier", Journal of Applied Physics, vol. 29, no. 9, September 1958, pp. 1321-1331.
A very good example of noise calculations for a complex electronic device.

27. J. S. Hey and V. A. Hughes, "A method of calibrating centimetric radiometers using a standard noise source", Proc. IRE, vol. 46, no. 1, January 1958, pp. 119-121.
Primary point of interest is use of a precision noise source of variable apparent temperature.

28. N. Houlding, "Mixer crystal noise", Proc. IRE, vol. 46, no. 5, May 1958, pp. 917-918 (Correspondence).
Some interesting comments on Appendix II of the paper by Messinger and McCoy[39] on the derivation of crystal mixer noise temperature. Goes into some detail on effects of mismatching both signal and image terminations.

29. R. A. Huggins, "Cascading traveling-wave tubes", Huggins Laboratories Engineering Notes, no. 6, May 1956.
Special problems of saturation of second TWT by the noise output of the first TWT.

(V. A. Hughes: see J. S. Hey.)

30. Institute of Radio Engineers, "Standards on electron devices: methods of measuring noise", Proc. IRE, vol. 41, no. 7, July 1953, pp. 890-896.
Most of the material is on the measurement of the noise figure. Not very thorough on definitions, nor very explicit.

31. _____, "Standards on receivers: Definitions of terms, 1952", Proc. IRE, vol. 40, no. 12, December 1952, p. 1684.
Definitions of several terms important to noise calculations are given, but all of these terms are more fully discussed in the preceding reference.

32. ____, "IRE standards on methods of measuring noise in linear two-ports, 1959", Proc. IRE, vol. 48, no. 1, January 1960.
A very thorough discussion of the techniques of measuring noise. The only noise factor covered is the one referred to the standard temperature. The only noise temperature mentioned is the "effective input noise temperature". The definitions of these terms, as well as associated quantities such as gain, noise bandwidth, etc., are very precise and lucid.

33. International Telephone and Telegraph Corporation, "Radio noise and interference", Reference Data for Radio Engineers, Fourth Edition, IT and T, New York, 1956, pp. 762-771.
Several useful formulas, definitions, and charts.

(Julian K. Knipp see Donald R. Hamilton.)

34. Harry Kruter, "Notes on noise figure theory and measurement", Report No. NADC-EL-52110, Aeronautical Electronic and Electrical Laboratory, U. S. Naval Air Development Center, Johnsville, Pa., 5 September 1952. (ASTIA Code: AD71824)
"This report attempts to clarify the relationship between narrow-band and wide-band noise-figure theory and measurements. It may be applied to the over-all noise figure measurement of radar duplexers and receivers. Considers situation in which gain of image channel is different from that of desired channel."

(J. B. Horner Kuper: see Donald R. Hamilton.)

35. Herbert J. Laskin, "Microwave detectors for measurement of relative power levels", PRD Reports, Polytechnic Research and Development Co., Inc., vol. 3, no. 1, July 1954.
Some material on minimum detectable signal power of crystal detectors and bolometers.

36. James L. Lawson and George E. Uhlenbeck, eds., Threshold Signals, vol. 24, MIT Radiation Lab Series, McGraw-Hill Book Company, Inc., New York, 1950.
One chapter is devoted exclusively to receiver noise to include antenna noise.

(B. J. Leon: see also E. Maxwell.)

(Elaine L. Luloff: see Robert Saul.)

37. E. Maxwell and B. J. Leon, "Absolute measurement of receiver noise figures at UHF", IRE Trans, vol. MTT-4, no. 2, April 1956, pp. 81-85.
Although primarily concerned with measurement techniques,

there is some material of interest on temperature variation along a transmission line.

38. George C. Messenger, "Cooling of microwave crystal mixers and antennas", IRE Trans, vol. MTT-5, no. 1, January 1957, pp. 62-63.
Brief discussion of the improvement in receiver sensitivity obtained by temperature reductions for the antenna and crystal mixer. Equations showing temperature dependence of the noise figure of the mixer are given.

39. ______ and C. T. McCoy, "Theory and operation of crystal diodes as mixers", Proc. IRE, vol. 45, no. 9, September 1957, pp. 1269-1283.
Material in detail on mixers. Of particular interest were two sections: one on effects of crystal noise temperature on noise figure, and the other on the minimization of receiver noise figure.

40. Microwave Associates, Inc., Silicon Diodes for Microwave Receivers, Catalog 58B.
Contains some material on mixer and detector noise and how this is affected by such things as bandwidth.

(S. M. Molivdas: see also S. H. Moss.)

41. Carol G. Montgomery, Technique of Microwave Measurements, vol. 11, MIT Radiation Lab Series, McGraw-Hill Book Company, Inc., New York, 1947.
Gives many basic definitions and some material on measurement techniques. Confusing on problem of source temperatures.

42. S. H. Moss and S. M. Molivdas, "The transformation of the noise temperature of a source across an isothermal passive linear network", GRS 3/SW/69, Central Radio Bureau (England), 9 April 1953. (ASTIA Code AD108715)
Arrives at the same result as the one given in this study by another line of reasoning.

43. W. W. Mumford and R. L. Schafersman, "Data on the temperature dependence of X-band fluorescent lamp noise sources", IRE Trans, vol. MTT-3, no. 6, December 1955, pp. 12-17.
Describes techniques of measuring source temperatures when the source is a fluorescent tube, and discusses some of the results obtained. Variation between tubes, and between different times for the same tube, were observed.

44. C. T. McCoy, "Present and future capabilities of microwave crystal receivers", Proc. IRE, vol. 46, no. 1, January 1958, pp. 61-66.

"The lower limits of receiver noise are explained in terms of the fundamental physical constants of vacuum tubes and microwave crystal rectifiers. With negative-grid vacuum tubes, the receiver noise, expressed in absolute temperature units, can be about 30°K at 10 Mc, but increases to about 1000°K at 1000 Mc. For crystal superheterodyne at all frequencies below 10,000 Mc, the receiver noise can be down to 600°K, limited only by the crystal mixer. Above 10,000 Mc the crystal rectifier parasitic elements---spreading and barrier capacitance---cause the receiver noise to increase rapidly to values of approximately 7000°K at 70,000 Mc. For the future, high-mobility semiconductors and new rectifier geometry promise substantial reduction of the parasitics. Also, a cooling mechanism promises limitless reduction in noise; a receiver noise of 150°K for all frequencies below 100,000 Mc seems feasible."

(_____: see G. C. Messenger.)

45. A. L. McWhorter and F. R. Arams, "System-noise measurement of a solid-state maser", Proc. IRE, vol. 46, no. 5, May 1958, pp. 913-914 (Correspondence).

Discusses briefly some special problems encountered in determining effective input noise temperature of a complete system using a three-level solid-state maser. Because the noise introduced by the device under measurement is so small, special care must be taken not to introduce errors.

46. Arnold Newton and John Ebert, "Noise figure and some measurement aspects", PRD Reports, Polytechnic Research and Development Co., Inc., vol. 2, no. 1, April 1953.

Primarily concerned with instrumentation problems--noise sources (hot resistance, noise diode, gas discharge, and impulse noise generator), transit time correction for a noise diode, etc.

47. D. O. North, "The absolute sensitivity of radio receivers", RCA Review, vol. 6, January 1942, pp. 332-344.

One of the early works in the field that introduced the noise figure and absolute sensitivity (output signal-to-noise ratio equal to unity).

(_____: see H. T. Friis.)

48. Kenneth A. Norton and Arthur C. Omberg, "The maximum range of a radar set", Proc. IRE, vol. 35, no. 1, January 1947, pp. 4-24.
The topic of most interest to this study was the material on the effects of external noise and the external noise factor of the antenna.

49. B. M. Oliver, "Noise figure and its measurement", Hewlett-Packard Journal, vol. 9, no. 5, January 1958, pp. 3-5 (see also H. C. Poulter).
Brief discussion of some of the theory of the noise figure, to include source temperature considerations, measurement, and effects of spurious responses.

(Arthur C. Omberg: see Kenneth A. Norton.)

50. J. L. Pawsey and R. N. Bracewell, Radio Astronomy, Oxford at the Clarendon Press, 1955.
A part of one chapter is devoted to receiver noise and sensitivity as well as antenna temperature.

51. Polytechnic Research and Development Co., Inc., "Detection and power measurement", PRD Microwave Test Equipment, Catalog E-8, 1958.
Discusses microwave power measurements, using both crystals and bolometers, with comments on noise and sensitivity, and errors caused by noise.

52. Howard C. Poulter, "An automatic noise figure meter for improving microwave device performance", Hewlett-Packard Journal, vol. 9, no. 5, January 1958 (See also B. M. Oliver).
Describes theory of operation and use of an automatic noise-figure meter designed to operate with either a gas discharge noise source or temperature-limited diode source. Measurements can be made on a manual basis or a swept basis. Further information on this topic is contained in "Additional conveniences for noise figure measurements", Hewlett-Packard Journal, vol. 10, no. 6-7, February-March 1959.

53. W. L. Pritchard, "Notes on a crystal mixer performance", IRE Trans, vol. MTT-3, no. 1, January, 1955, pp. 37-39.
Discusses mixer crystal noise temperature and effects of matching condition at input and output. Also gives optimum i-f source impedance.

54. Louis N. Ridenhour, Radar System Engineering, vol. 1, MIT Radiation Lab Series, McGraw-Hill Book Company, Inc., New York, 1947.
An introduction to the theory of the minimum detectable signal as well as to some statistical concepts of noise.

(William L. Root: see Wilbur B. Davenport, Jr.)

(B. Salzberg: see J. C. Greene.)

(E. W. Bard: see J. C. Greene.)

55. Robert Saul and Elaine L. Luloff, "Microwave noise figure measurements using a signal generator", The Microwave Journal, vol. 2, no. 4, April 1959, pp. 33-36.
Describes the actual technique of using a signal generator to obtain noise figures. The treatment of the problem of source temperature is not very explicit.

(R. L. Schafersman: see W. W. Mumford.)

56. Karl R. Spangenberg, Fundamentals of Electron Devices, McGraw-Hill Book Company, Inc., New York, 1957.
A chapter is devoted to noise in electron devices.

57. G. C. Stanley, Jr., "Noise figure measurement techniques", Internal Memorandum [DA 36(039)sc-73151], Systems Techniques Laboratory, Stanford Electronics Laboratories, Stanford University, Stanford, California.
Primarily concerned with measurement techniques, but does contain some definitions of interest.

58. _____, "Noise figure measurements of several S-band traveling-wave tubes", Technical Report No. 503-2 [DA 36(039)sc 73151], Stanford Electronics Laboratories, Stanford University, Stanford, California, 21 April 1958.
Several definitions of noise source temperatures.

59. Peter D. Strum, "Some aspects of mixer crystal performance", Proc. IRE, vol. 41, no. 7, July 1953, pp. 875-889.
"An investigation of crystal noise characteristics is reported, and it is shown that there is an optimum intermediate frequency for minimum noise figure. The design criteria for minimum receiver noise figure are shown."

60. _____, "Considerations in high-sensitivity microwave radiometry", Proc. IRE, vol. 46, no. 1, January 1958, pp. 43-53.
The effects of internal receiver and antenna noise are considered as well as other characteristics, such as gain fluctuations that are primarily problems in the receiver designed for radio astronomy work. An analysis of the signal-to-noise performance of the linear, square-law, and general-law detectors is presented.

61. _____, "A note on noise temperature", IRE Trans., vol. MTT-4, no. 3, July 1956, pp. 145-151.
"The effective noise temperature of the output impedance of a lossy passive network at an arbitrary noise temperature connected to one or more resistive loads at arbitrary noise temperature lies between the highest and lowest of these noise temperatures, as determined by the losses between the output terminals and the loads. The determination of the effective noise temperature of a gas-discharge noise generator over a wide frequency range is simplified by the substitution of a loss measurement for the more difficult noise temperature measurement. For minimum-noise radar applications care must be used in considering the excess noise of crystal mixers and gas-discharge duplexers. The influence of galatic radiation on a receiving system is such that there is an optimum frequency in the region of 200 to 600 Mc for minimum "operating noise figure". Typical examples of radio-astronomy measurements are amenable to analysis of the type given. Finally, several corrections to measured noise figure are analyzed."

62. Frederick Emmons Terman, Electronics and Radio Engineering, McGraw-Hill Book Company, Inc., New York, 1955.
A general reference book that gives some definitions and equations of interest but no treatment on "temperature".

63. Henry C. Torrey and Charles A. Witmer, Crystal Rectifiers, vol. 15, MIT Radiation Lab Series, McGraw-Hill Book Company, Inc., New York, 1948.
Complete treatment of noise and sensitivity, although some of the material is out of date.

(George E. Unlenbeck: see James L. Lawson.)

64. George E. Valley and Henry Wallman, Vacuum Tube Amplifiers, vol. 18, MIT Radiation Lab Series, McGraw-Hill Book Company, Inc., New York, 1948.
Specific chapters of interest were "Amplifier sensitivity", "Minimal noise circuits", and "Measurement of noise figure".

65. John P. Van Duyne, "Noise limited receiver sensitivity measurement technique", The BRC Notebook, No. 20, Boonton Radio Corporation, Boonton, New Jersey, Winter 1959.
An interesting account of early methods of specifying receiver noise covering the limitations and errors of each technique. The methods covered are "equivalent noise sideband input", "standard output", and noise figure.

66. S. N. Van Voorhis, ed., Microwave Receivers, vol. 23, MIT Radiation Lab Series, McGraw-Hill Book Company, Inc., New York, 1948.
This work contains material on noise as it is found in nearly every stage of the receiver. Many practical examples are given, but the calculation of the system noise figure or sensitivity is not covered in great detail.

(G. Wade: see H. Heffner.)

(Henry Wallman: see George E. Valley.)

(Charles A. Witmer: see Henry C. Torrey.)

67. Aldert van der Ziel, Noise, Prentice-Hall, Inc., New York, 1954.
More than half of this book is of interest to this study although some of the material is difficult to understand. The remainder deals with the mathematical theory of random noise.

# SYSTEMS TECHNIQUES DISTRIBUTION LIST

September 1961

Commanding Officer
U.S. Army Signal Research and Dev't Laboratory
Fort Monmouth, New Jersey
1 Attn: U.S. Marine Corps Liaison Office, AO-4C, Bay 4D-119
1 Attn: Director of Research
1 Attn: RSD, Radio Relay Branch
1 Attn: U.S. CONARC Liaison Office
1 Attn: Chief, Meteorological Div., Surveillance Dept.
1 Attn: Director, Applied Physics Div., Surveillance Dept.
1 Attn: Chief, Advance Dev't Br. Radar Div., Surveillance Dept.
5 Attn: Solid State Devices Div. Electronic Components Res. Dept., Attn: Nathalie Mooney Room 4C31?
1 Attn: Chief, Special Devices Br., Electronic Warfare Div., Surveillance Dept.
1 Attn: Chief, Electro-Magnetic Environment Div., GFR
1 Attn: Senior Scientist, Electronic Warfare Div., Surveillance Dept.
1 Attn: Chief, Advanced Techniques Br., Electronic Warfare Div., Surveillance Dept., Attn: Mr. H. Brett
1 Attn: Chief, Advanced Techniques Br., Electronic Warfare Div., Surveillance Dept.
1 Attn: Technical Documents Center Surveillance Dept.
1 Attn: Mail and Records, File Unit 2
1 Attn: Reports Distribution Unit, Electronic Warfare Div., Surveillance Dept.
1 Attn: SIGRA/SL-ADT-E

Commanding General
Countermeasures Division
DOT, USASSCS
Fort Monmouth, New Jersey
1 Attn: E. Allen

Chief,
West Coast Office
U.S. Army Signal Res. and Dev't Lab.
75 South Grand Ave. Bldg. 13
1 Pasadena, California

Signal Corps Liaison Office
Massachusetts Ave.,
Bldg. 26-131
Cambridge, Massachusetts
1 Attn: Mr. A.D. Bedrosian

Commanding General
U.S. Army Ordnance Missile Command
Redstone Arsenal, Alabama
1 Attn: ORDXM-DR

Commander
Army Rocket Guided Missile Agency
Redstone Arsenal, Huntsville, Ala.
1 Attn: ORDXR-WPE, Mr. Lindberg

Commanding Officer
U.S. Army Signal Missile Support Ag.
White Sands Missile Range
New Mexico
1 Attn. SIGWS-MEW
1 Attn: SIGWS-FC

Commanding General
U.S. Army Electronic Proving Ground
Fort Huachuca, Arizona
1 Attn: Technical Library

Commanding Officer
Office of Naval Research
Branch Office
1000 Geary Street
1 San Francisco, California

Director
Naval Research Laboratory
Washington 25, D. C.
1 Attn: Code 2027
1 Attn: Code 5430 (Countermeasures Br.)

Electronic Warfare Systems Br. OP-352
Office of the Chief of Naval Ops.
Department of the Navy
1 Washington 25, D. C.

Commanding Officer & Director
U.S. Naval Electronics Laboratory
San Diego 52, California
1 Attn: Library

Commander
U.S. Naval Missile Center
Point Mugu, California
1 Attn: 5321

Navy Department
U.S. Naval Avionics Facility
Indianapolis 18, Indiana
1 Attn: Station Library

Chief
Research & Development Division
Office of the Chief Signal Officer
Department of the Army
Washington 25, D. C.
1 Attn: SIGRD-5A

Office of the Chief Signal Officer
Department of the Army
Washington 25, D. C.
1 Attn: SIGRD-9

Director of Research & Technology
Headquarters, USAF
Washington 25, D. C.
1 Attn: AFDRT-ER

Commander
Aeronautical Systems Division
Wright-Patterson Air Force Base
Ohio
1 Attn: WADPRO
1 Attn: WWRNRE-1
1 Attn: ASRNC
1 Attn: ASAPRD-DIST
1 Attn: WWRNEV-1
1 Attn: ASRK

Commander
Air Technical Intelligence Center
Wright Patterson Air Force Base
Ohio
1 Attn: AFCIN-4E-1C
2 Attn: AFCIN-4C3B
1 Attn: AFCIN-4C-1B

Executive Director
Air Force Office of Scientific Res.
Washington 25, D. C.
1 Attn: SRYA

Commander
Air Proving Ground Command
Eglin Air Force Base, Florida
1 Attn: ADJ/TRB

Commander
Air Force Missile Dev't Center
Holloman Air Force Base
New Mexico
1 Attn: MDV

Commander
Headquarters, USAF Security Service
Kelly Air Force Base
San Antonio, Texas
1 Attn: CLR

Commander
Rome Air Development Center
Griffiss Air Force Base
Rome, New York
1 Attn: RCWIL
1 Attn: Document Library
1 Attn: RCLS
1 Attn: RCRMSA
1 Attn: RCWED, T.J. Domurat
1 Attn: RCWEDS
1 Attn: RCUEA
1 Attn: RCWED-2

Operations Analysis
Hqs., Strategic Air Command
Offutt Air Force Base
Nebraska
1 Attn: Mr. Eugene A. Jackson

Commander
Air Force Cambridge Research Center
L. G. Hanscom Field
Bedford, Massachusetts
1 Attn: Electronic Research Lab.(CRR)

Air Force Command & Control Dev't Division
Attn: CCSIL
Laurence G. Hanscom Field
1 Bedford, Massachusetts

Commander
Air Force Cambridge Research Labs.
L. G. Hanscom Field
Massachusetts
1 Attn: CRRCPV

Commander
AF Ballistic Missile Division
Hq., Air Res and Dev't Command
USAF, Air Force Unit Post Office
Los Angeles 45, California
1 Attn: WDAT

Commander
Air Research and Dev't Command
Andrews Air Force Base
Washington, D. C.
1 Attn: RDR-2

Department of Defense
Defense Communications Agency
Washington 25, D. C.
1 Attn: Code 711, Fred P. Miller

Director
Weapons System Evaluation Group
Room 1E875, The Pentagon
1 Washington 25, D. C.

Central Intelligence Agency
2430 E Street
Washington 25, D. C.
1 Attn: OCR Standard Distribution

Advisory Group on Electron Tubes
346 Broadway Street
1 New York 13, New York

Commander
Armed Services Tech. Info. Agency
Arlington Hall Station
Arlington 12, Virginia
11 Attn: TIPCA

Ordnance Corps
Diamond Ordnance Fuze Laboratories
Washington 25, D. C.
1 Attn: DOFL Library
Rm. 211, Building 92

The Director
U. S. National Bureau of Standards
Washington 25, D. C.
1 Attn. Section 14.1, G. Shapiro

Director
National Security Agency
Fort George G. Meade, Maryland
1 Attn: Technical Documents
1 Attn: RADE-34, Mr. H. Sonneler

Chief
U.S. Army Security
Arlington Hall Station
Arlington 12, Virginia
1 Attn: IACON

Chief
U.S. Army Security Agency
Arlington Hall Station
Arlington 12, Virginia
1 Attn: IADEV

Director
National Security Agency
3801 Nebraska Ave., N.W.
Washington 25, D.C.
1 Attn: C15

University of Chicago
Laboratories for Applied Sciences
Museum of Science and Industry
Chicago 37, Illinois
1 Attn: Library

Illinois Institute of Technology
Technology Center
Chicago 16, Illinois
1 Attn: Security Officer
Electronics Research Labs.

The Johns Hopkins University
Radiation Laboratory
1315 St. Paul Street
Baltimore 2, Maryland
1 Attn: Technical Reports Library

The University of Michigan
Cooley Electronics Laboratories
Dept. of Electrical Engineering
Ann Arbor, Michigan
1 Attn: Dr. B. F. Barton

Director, Research Division
College of Engineering
New York University
New York, New York
1 Attn: Mr. R. F. Cotellessa
Contract No. DA36-039 sc-74990
File No. 0040-PM-58-91

The Ohio State University
Research Foundation
1314 Kinnear Road
Columbus 12, Ohio
1 Attn: Carlos Brewer, Security Off

Stanford Research Institute
Document Center
Menlo Park, California
1 Attn: Acquisitions

Syracuse University
Research Corporation
1 Syracuse, New York

Syracuse University
Research Institute
Collendale Campus
1 Syracuse 10, New York

Defense Research Laboratory
The University of Texas
P. O. Box 8029
1 Austin 12, Texas

Military Physics Res. Laboratory
The University of Texas
Box 8036, University Station
Austin 12, Texas
1 Attn: Mrs. Olga C. Williams

Airborne Instruments Laboratory
A Division of Cutler-Hammer, Inc.
Walt Whitman Road
Melville, New York
1 Attn: Librarian

American Electronic Labs., Inc.
116 N. 7th Street
1 Philadelphia 6, Pennsylvania
Contract No. DA36-039 sc-78166
File No. 0236-PM-58-91

Cornell Aeronautical Labs.
4455 Genesee Street
Buffalo 21, New York
1 Attn: D. K. Plummer

General Electric Company
Research Laboratory
P. O. Box 1088
Schenectady, New York
1 Attn: R. L. Shuey, Mgr.
Information Studies Section

Granger Associates
974 Commercial Street
1 Palo Alto, California
Contract No. DA36-039 sc-84533
File No. 19204-PM-59-93-93

HRB-Singer Inc.
1 State College, Pennsylvania
Contract No. DA36-039 sc-78296
File No. 15931-PM-59-91-91

HRB-Singer, Inc.
Science Park
State College, Pennsylvania
1 Attn: R. George Herlt

Hughes Aircraft Company
Documents Center
6/c2048, Florence at Teale Street
Culver City, California
1 Attn: Technical Library

International Telegraph and Telephone
Corporation
ITT Laboratories Division
492 River Road
Nutley, New Jersey
1 Attn: J. LeGrand

International Business Machines Corp.
Federal Systems Division
Tiggs County
Owego, New York
1 Attn: Technical Reports Center

Jansky and Bailey, Inc.
1339 Wisconsin Ave., N.W.
Washington 7, D. C.
1 Attn: Mr. J. Renner

Lockheed Aircraft Corporation
86 So. Cobb Drive
1 Marietta, Georgia

Loral Electronics Corp.
825 Bronx River Avenue
New York 72, New York
1 Attn: Mr. T. McLaughlin
Contract No. DA36-039 sc-78140
File No. 0319-PM-58-91

Loral Electronics Corporation
Missiles Technology Division
12791 Newport Avenue
Tustin, California
1 Attn: Security Officer

Motorola, Inc.
1450 N. Cicero Ave.
1 Chicago 51, Illinois

Motorola, Inc.
8330 Indiana Avenue
1 Riverside, California
Contract No. DA36-039 sc-81239
File No. 370-PM-56-91

North American Aviation, Inc.
Autonetics Technical Library
Los Angeles 45, California
1 Attn: J. R. Bracha

Packard Bell Electronics
P.O. Box 337
1 Newbury Park, California

Radio Corporation of America
75 Varick Street
New York 13, New York
1 Attn: H.C. Myers, Jr.
Contract No. DA36-039 sc-78114
File No. 0317-PM-58-91

Radio Corporation of America
WCM and SMD Engineering Lib., 306/2
8500 Balboa Blvd.
Van Nuys, California
1 Attn: L. R. Hund, Librarian

The Rand Corporation
1700 Main Street
1 Santa Monica, California

Revere Copper and Brass, Inc.
Foil Division
196 Diamond Street
Brooklyn 22, New York
1 Attn: Vincent B. Lane

Sperry Gyroscope Company
Division of Sperry Rand Corporation
Great Neck, New York
1 Attn: N. Meyers D7

Lockheed Electronics Co.
Stavid Division
U. S. Highway No. 22
Plainfield, New Jersey
1 Attn: C. L. Opitz

Commanding Officer
U. S. Army Signal Elec. Res. Unit
P.O. Box 205
1 Mountain View, California

Sylvania Electronic Systems
Div. of Sylvania Elec Prod., Inc.
Waltham Laboratories
100 First Avenue
1 Waltham 54, Massachusetts

*Commanding Officer
U.S. Army Signal Research and
Development Laboratory
Fort Monmouth, New Jersey
3 Attn: Chief, Security Division (for
retransmittal to accredited
British and Canadian Gov't
representative)

**Commander
Wright Air Development Division
Wright-Patterson Air Force Base
Ohio
1 Attn: WWRNEA
Maj. Lawrence Politzer

**Ohio University
College of Applied Science
Athens, Ohio
1 Attn: H.L. Hoffee

***Air Force Development Field Rep.
San Francisco Bay Area
Air Research and Dev't Command
1176 Los Altos Avenue
Los Altos, California
1 Attn: Major Otis N. Hill

+Boeing Airplane Company
Aero-Space Division
Library 13-84
1 Seattle 24, Washington

* Signal Corps Contract
DA36(039) sc-78296 reports only
** Unclassified reports only
*** Quarterly Status Reports only
\+ AF33(616)-6207 reports only